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San Pedro Riparian National Conservation Area (SPRNCA) Water Needs Study

Final Report Draft

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DRAFT

This document is a preliminary draft of the final report. It is for review purposes only by the members of the USPP Technical Sub-committee and the scientists appointed by the USGS to review the report for its inclusion in a USGS publication. Data in this report not previously published are preliminary and may be subject to change.

Summary

The purpose of this portion of the Water Needs Study is to provide improved estimates of groundwater, or consumptive, use by the riparian vegetation within the San Pedro Riparian National Conservation Area (SPRNCA). Such knowledge will greatly enhance understanding of the riparian vegetation water needs and the role of riparian vegetation groundwater use in the Upper San Pedro Basin water budget. Our approach was to make new, direct measurements of evapotranspiration (ET) from dominant ecosystem types within the SPRNCA that are the principal components of the riparian groundwater demand. Coupled with these measurements of ET, we also studied how ET was partitioned into surface or groundwater sources. We then combine these revised and refined estimates of ecosystem water use with a new vegetation map of the SPRNCA to extrapolate the local measurements to the entire SPRNCA for estimates of total groundwater use by vegetation. The following improvements were made to the most recent estimates of riparian corridor groundwater use along the San Pedro River by Goodrich et al. (2000):

- **Mesquite woodland and shrubland**: Mesquite is the most spatially extensive vegetation type within the SPRNCA, yet its water use was identified as the most uncertain. Goodrich et al. (2000) used one year of observations from a mesquite shrubland to estimate this component. The current study made multi-year ET observations from a mature mesquite woodland and a mesquite shrubland and found that: 1) both used substantially more water than previously estimated, and 2) their water use was nearly equal on a per unit canopy area basis between sites. Stable isotope measurements revealed considerable seasonal variation in the proportion of mesquite transpiration derived from groundwater. Mesquite used a combination of surface (recent precipitation), deeper vadose zone, and groundwater sources, and use of these sources depended on their availability through the season. There was a tendency for less proportional groundwater use in mesquite stands that had comparatively less access to groundwater (deeper water table). Nevertheless, mesquite on the floodplain terraces used substantial quantities of groundwater. Total annual groundwater use at the Charleston Mesquite site determined by two semi-independent methods (water budget method and isotope partitioning method) were not in agreement. Recent studies at this site reveal that mesquite can redistribute significant amounts of water between deep and shallow soil layers during winter and summer months through its extensive root system (Hultine et al. in press). At this time, we do not have a way to quantify how much water is redistributed by the mesquite nor whether the source of deep vadose zone moisture was from precipitation or groundwater sources. The mass balance approach did not account for the redistribution effects and resulted in mesquite woodland seasonal groundwater use amounts of 490 mm in 2001, 390 mm in 2002, and 510 mm in 2003, which were about 30% higher than the estimates based on isotopes (available for only 2001 and 2002). Since we determined riparian corridor consumptive use in 2003, we chose to use the mass balance value of 510 mm, which is likely a conservatively high amount

since possible redistribution of previous wintertime rainfall was ignored with this approach.

- **Cottonwood forest**: Goodrich et al. (2000) estimated cottonwood consumptive use using limited 1997 synoptic-period sapflow observations of cottonwoods along a perennial reach. These measurements were scaled up to growing season totals by using a calibrated Penman-Monteith model. The current study measured sap flow over most of the 2003 growing season to estimate transpiration along a perennial and an intermittent reach. Cottonwood forest at the perennial reach transpired a total of 970 mm, about 20% more water on a per canopy area basis than the 1997 estimates. It is likely that the Goodrich et al. (2000) estimates of cottonwood forest transpiration were lower than that found in the current study due to the shorter growing season in 1997 (by about 30 days) and because Goodrich et al. (2000) did not account for nocturnal sap flow, which we found to be significant. Cottonwood forests along the intermittent reach used 480 mm in 2003, considerably less water than at the perennial reach, and had greatly reduced rates of transpiration as the water table levels declined in the pre-monsoon season. Low rates of cottonwood forest transpiration at the intermittent reach were a result of physiological stress acting on stomatal conductance of leaves and the sparse density of leaves at the stand level. Roughly 40% of the cottonwood forests in the SPRNCA were classified as being on intermittent reaches.

- **Sacaton**: Goodrich et al (2000) assumed that all sacaton grasslands did not use groundwater. The current study revealed that a sacaton grassland did use approximately 370 mm of groundwater in 2003 when the depth to groundwater was less than ~ 3 m. Using LiDAR measurements and GIS, the area where the land surface elevation was within 3 m of the river stage was used as an estimate of the area where the depth to groundwater was less than 3 m. The amount of sacaton within this area was determined by intersecting this delineated region with the vegetation map. Only about 30% of the total sacaton grassland area within the SPRNCA fell within this region. The sacaton within the 3 m depth to groundwater boundary was assumed to have the groundwater use of the sacaton measured in the current study.

- **Open channel evaporation**: Previously, open channel evaporation was estimated by computing a seasonal potential evaporation rate using meteorological data and multiplying this by an assumed reduction factor to account for the effect of shading and entrenchment that would reduce this rate relative to an open water estimate. The current study made *in-situ* measurements of small pan evaporation distributed throughout the near-stream environment to compute a reduction factor over a limited period. Using this relationship, we computed an open water evaporation of 1210 mm for 2003.

- **Understory species**: Previous studies have ignored the potential use of groundwater by understory, near-stream vegetation elements. We made observations of seep willow transpiration using sapflow methods as a preliminary step toward understanding the relative magnitude of its groundwater use, and we used transect information from ASU to estimate how much seep willow lies within the SPNRCA. Our measurements indicated that seep willow transpiration on a per unit canopy area basis was as large in magnitude as any of the major groundwater using vegetation types studied in this report. However, since total seep willow cover along the SPRNCA is estimated to be low compared to other vegetation types, consumptive use by seep willow is one of the smallest of all the components in the SPRNCA consumptive use.

- **Vegetation mapping**: The use of a new vegetation map produced by the Army Corps of Engineers resulted in large changes in the computed amounts of vegetation within the SPRNCA relative to those used by Goodrich et al. (2000). The new map provided a range (minimum – maximum) for percent cover of the dominant vegetation type in each polygon; therefore, the exact amount of vegetation could not be calculated. Also, it was necessary to clip the new map to the approximate extent of the riparian corridor. We used reach-level information provided by ASU to enumerate the amount of cottonwood/willow forest that occurred along perennial or intermittent reaches. An additional calculation delineated the sacaton grasslands that occurred in regions with elevations less than 3 m of the river stage in order to delineate sacaton that used groundwater.

- **ET tool:** A user-friendly interface was developed for ArcView GIS that allows for easy manipulation of a vegetation map and projection of the seasonal demand of groundwater-using vegetation. The tool calculates the total amounts of different types of phreatophytic vegetation from a vegetation map of the riparian corridor of the Upper San Pedro River and then multiplies these amounts by the appropriate seasonal groundwater demand per unit area of vegetation to calculate the total groundwater use. The tool will be ready for distribution on CD-ROM by May, 2004.

- **Total SPRNCA consumptive use:** Total vegetation amounts were multiplied by their respective consumptive use rates as determined by measurements made in 2003 to determine riparian corridor consumptive use (Section 4). Mesquite consumptive use was the dominant component of the water budget with cottonwood/willow, open water, sacaton, and salt cedar, respectively, of decreasing importance. Our 2003 estimate for the consumptive use from the International border to the Tombstone gage (for the Sierra Vista Sub-basin) was 9,039,000 –11,064,000 $m^3\ yr^{-1}$ (7330 ac-ft/yr –8970 ac-ft yr^{-1}), 11 - 36 % higher than Goodrich et al. (2000) due to the combination of using the new vegetation map and the new water use estimates (Table 4-7) . Corell and others' (1996) estimate of 9,498,000 $m^3\ yr^{-1}$ (7700 ac-ft) for riparian consumptive use within the Sierra Vista Sub-basin fits within the range of our estimates. We stress the importance of recognizing the influence of interannual climatic variability on these estimates. For example, with just three years of mesquite ET data, we found that the mesquite water use from year to year was quite variable, as much as 22% less relative to 2003. It is reasonable to expect that the functioning of other vegetation communities are similarly impacted by climate variability and that the annual SPRNCA consumptive use also fluctuates to a similar degree.

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1 Introduction

1.1 Rationale and Background

The Upper San Pedro Partnership (USPP) is a consortium of twenty agencies and organizations formed to ensure the area's long-term water needs are met. The USPP established a planning goal to "ensure an adequate long-term groundwater supply is available to meet the reasonable needs of both the areas residents and property owners (current and future) and the San Pedro Riparian National Conservation Area (SPRNCA)". One part of that planning effort was the SPRNCA Water Needs Study. The intent of the SPRNCA Water Needs Study was not only to define the hydrologic requirements of the SPRNCA itself, but also to provide information regarding possible water use effects of management actions taken to reduce the consumptive water uses within the SPRNCA without resulting in any negative effects on riparian resources.

The Water Needs Study was a interdisciplinary and multi-investigator effort to accomplish three objectives: 1) To determine the temporal and spatial water needs of riparian vegetation within the SPRNCA, 2) To quantify the total consumptive water use of riparian vegetation within the SPRNCA, and 3) To determine the sources of water consumed by key riparian plant species within the SPRNCA. The research involved the work from four separate entities: the United States Department of Agriculture's Agricultural Research Service (USDA-ARS), the University of Wyoming (UW)[1], the University of Arizona (UA), Arizona State University (ASU) and the United States Geological Survey (USGS). This portion of the final report summarizes the activities and results of USDA-ARS, UW, and UA efforts during the three years of the study.

The combined research team of USDA-ARS, UW, and UA had the primary role in the SPRNCA Water Needs Study to improve estimates of the water use by riparian vegetation and to identify the sources of that water. In order to do this, the main experimental objectives, developed in coordination with the USPP were to:

1) Quantify the consumptive water use of riparian mesquite woodlands;
2) Quantify environmental factors that are likely to influence mesquite water use;
3) Quantify the consumptive water use of understory vegetation within the cottonwood/willow stands and the evaporation from the free water surface within SPRNCA;
4) Identify the evaporation water source for the dominant vegetation communities;
5) Quantify the total consumptive groundwater use from the regional aquifer by riparian vegetation within SPRNCA; and,

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[1] Dr. Williams, one of the Study's main researchers, and his students were located at the start of this project at the University of Arizona. They have recently moved to the University of Wyoming.

6) Develop a GIS-based management tool for determining how changes in riparian vegetation composition will likely alter total consumptive regional aquifer groundwater use of riparian vegetation.

These objectives followed from previous work done to estimate water use for the Upper San Pedro River and were designed to refine our knowledge of riparian vegetation functioning so that improved estimates can be made.

Goodrich et al. (2000) reported the most recent work on this issue, and it was the foundation for this study. Their study synthesized the results of the interdisciplinary SALSA Program in order to make the first estimates of riparian corridor groundwater use based on *in situ* data for a portion of the SPRNCA. Most of the estimates made prior to Goodrich et al. (2000) were derived from groundwater modeling studies that indirectly infer or model riparian groundwater use in a highly-simplified manner (Kreager-Rovey, 1974; Freethey, 1982; Rovey, 1989; Vionnett and Maddock, 1992; Corell et al., 1996). Prior to Goodrich et al. (2000), Corell et al. (1996) estimated ET by using the difference between baseflow in winter and summer at the USGS surface water gages at Palominas, Charleston, and Tombstone. Using entirely different approaches, both estimates are surprisingly similar (Table 1-1). The estimates of Corell et al. (1996) also include losses due to agricultural pumping.

Table 1-1. Previous Upper San Pedro annual riparian consumptive use estimates for the Sierra-Vista Sub-basin.

Corell et al. (1996)	9498000 m^3 (7700 ac-ft)[a]
Goodrich et al. (2000)	8130000 m^3 (6591 ac-ft)[b]

[a]From the start of the perennial reach upstream of the Palominas gage to the Tombstone gage.
[b]From the international border to the Tombstone gage

Our approach to estimating consumptive use was to refine water use estimates for the key ecosystem types found within the SPRNCA using hydro-ecological measurements of evapotranspiration and plant water sources. Next, we combined these revised, and sometimes novel, estimates with a new vegetation map developed for the SPRNCA in 2000 to determine riparian consumptive use. Following many of the recommendations of Goodrich et al. (2000), the main ecosystems of interest were mesquite (*Prosopis velutina*) woodlands and the cottonwood (*Populus fremontii*) forest, but we were also able to study an additional sacaton (*Sporobolus wrightii*) grassland and mesquite shrubland through a new collaborative effort with the University of Arizona. Additionally, we also carried out pioneer studies of open water evaporation and the transpiration of a major understory plant species, seep willow (*Baccharis salicifolia)*. In order to provide better access to these results, a GIS-based tool was created that allows the user to quantify how the water use will likely change as the result of vegetation cover change (Appendix 1). Finally, we performed a comparison of meteorological variables collected from three meteorological sites to determine how certain parameters relevant to the evaporation process and future modeling studies varied at different locations within the SPRNCA (Appendix 2).

2 Methods

2.1 Mesquite Woodland

2.1.1 Site Description

The Charleston Mesquite (CM) study site is located on the east side of the San Pedro River at an elevation of 1200 m, approximately 16 km northeast of Sierra Vista, Arizona (Fig. 2-1). The site is co-located with one of the Water Needs Study Transects. The study site is a dense woodland dominated by velvet mesquite (*Prosopis velutina*). The understory is primarily sacaton grass (*Sporobolus wrightii*) with some greythorn shrubs (*Zizyphus obtusifolia*) and various annual herbaceous species. The average canopy cover is ~70%. The measured Leaf Area Index (LAI) (LI-2000, LI-COR, Inc., Lincoln, NE) ranges from an average (n = 40) of ~1.0 prior to leaf-out to ~1.6 during most of the growing season. The mean canopy height is approximately 7 m and the maximum canopy height ~10 m.

The deepest rooting depths of the understory plants have not been observed to be greater than 2 – 3 m, implying that they do not have access to the groundwater at a depth of ~10 m. Rooting patterns of non-riparian mesquite are quite varied and extensive (Heitschmidt et al., 1988) and have been described as “ubiquitous” (Gile et al., 1997). From cut-banks along the river near our site, we have observed mesquite roots extending both laterally near the surface and vertically all the way down to the water table. On the mesquite terrace, soils are sandy loams interspersed with layers of gravel and clayey material.

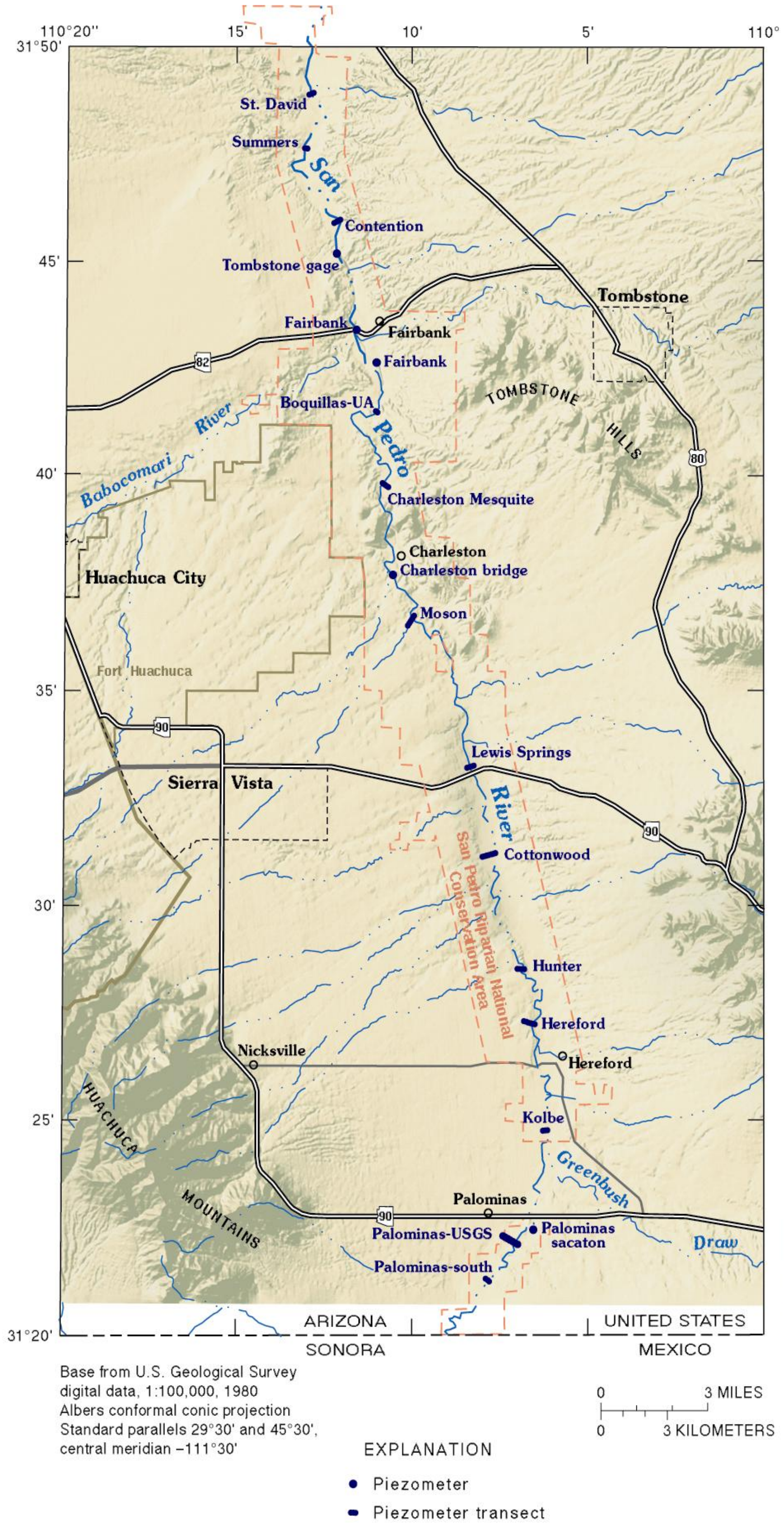

Figure 2-1. Map of Water Needs Study area and transects (courtesy of the USGS)

2.1.2 Metflux Instrumentation[2]

Evapotranspiration was measured using the eddy covariance technique throughout most of the active mesquite growing season in 2001, 2002 and 2003. Basic meteorological, soil moisture, and groundwater height data were also collected throughout most of each year. A three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific Inc., Logan UT) and an open path infrared gas analyzer (IRGA; Model LI-7500, LI-COR, Inc., Lincoln, NE) mounted at a height of 14 m at the top of a scaffolding tower measured the three components of the wind velocity vector, sonic temperature, and the densities of water vapor and CO_2. These were sampled at 10 Hz by a datalogger (CR5000, Campbell Scientific, Logan, UT) which also calculated their 30-minute covariances using block Reynolds averaging. Surface fluxes were later calculated off-line, after performing a two-dimensional coordinate rotation and accounting for density fluctuations (Webb et al., 1980). The sonic temperature was used to calculate sensible heat flux using the method suggested by Paw U et al. (2000), which accounts for a missing energy balance term associated with the expansion of air during evaporation under constant pressure. Fluxes measured when the wind was coming from a direction that was within 20° of behind the anemometer (~ 6 % of the data) were ignored due to possible interference from the anemometer support and the IRGA mounted behind the anemometer.

Basic meteorological measurements were made with a wind vane/anemometer (R.M. Young Co., Traverse City, MI) and a temperature/relative humidity probe (HMP35D, Vaisala, Helsinki, Finland) at a height of 13.5 m, and above-canopy net radiation was measured at a height of 9 m using a 4-component radiometer (Model CNR 1, Kipp & Zonen, Delft, The Netherlands) attached to a horizontal boom extending 4 m from the tower. Ground heat flux was measured with eight soil heat flux plates (REBS Inc., Seattle, WA) installed 0.05 m below ground level. Measurements of the rate of change of soil temperature above the heat flux plates (at 0.02 and 0.04 m) allowed calculation of the soil heat flux at the surface using estimates of the specific heat of the 0.05 m thick soil layer obtained with a thermal properties sensor (TP01, Hukseflux, Delft, The Netherlands). Additional meteorological measurements were made in cooperation with the Ft. Huachuca Met team.

Soil moisture was measured with twelve water content reflectometers (Model CS615, Campbell Scientific, Inc., Logan, UT) installed in profiles at depths of 0.05, 0.10, 0.20, 0.30, 0.50, 0.70 and 1.0 m. Two probes were installed at each of the five upper depths, and the reported data for these depths represent an average of the two. A network of piezometers was installed to measure fluctuations in the water table. Measurements of water table elevation were taken manually until the installation of pressure transducers (miniTROLL, In-Situ, Laramie, WY) in late June 2001, and periodically afterward to confirm accuracy of the transducers. A tipping bucket rain gage measured the precipitation at the top of the tower. Data from all the sensors were recorded on

[2] See Scott et al., 2004 for detailed methods and results of this study for the years 2001 and 2002.

dataloggers (Models 21X and CR5000, Campbell Scientific, Inc., Logan, UT) which were interrogated every 7-10 days by a laptop PC.

Studies using eddy covariance instrumentation commonly use the standard of energy balance closure to evaluate the accuracy and efficacy of their measurements (Wilson et al., 2002). Neglecting the heat stored in the biomass and the air below the sensors, the one-dimensional energy balance for the mesquite woodland can be written as:

$$R_n - G = \lambda E + H \tag{2.1}$$

where R_n is the net radiation, G is the soil heat flux, and λE and H are the latent (i.e., evapotranspiration multiplied by the latent heat of condensation) and sensible heat fluxes, respectively. As a measure of how well the energy balance was closed in our observations, Table 2-1 gives the results of a least squares regression between the sum of the turbulent fluxes, ($\lambda E+H$), relative to the available energy, (R_n-G), for 30-minute fluxes, and for daily total fluxes when fluxes were available for more than 24 half-hour periods in the day. If the intercept of the regression line close to zero, then the slope of the regression line indicates the degree of closure for the energy balance. In general, closure was moderate in this study with approximately 15% - 25% of the available energy unaccounted for at the half-hourly time scale and 0 – 20 % at the daily time scale. While not ideal, this is consistent with numerous other studies made using eddy covariance instruments (see Wilson et al. (2002) for a summary of this issue). Using daily average fluxes improves the energy balance, suggesting that there was a daily cycle in the (unmeasured) energy stored in the air and particularly, the biomass below the sensors (Blanken et al., 1997; Gu et al., 1999) which was approximately 7 - 15% of the available energy.

Table 2-1. Ordinary linear regression coefficients for energy balance closure

	n	Slope	Intercept	R^2
30-min values				
2001	9294	0.78	10.6	0.93
2002	9818	0.73	11.2	0.92
2003	10510	0.84	16.0	0.93
Daily means[b]				
2001	225	0.87	-1.3	0.92
2002	227	0.80	1.0	0.91
2003	231	0.99	-8.1	0.90

[b] for days with at least 24 half-hourly values of all energy balance components

One of the goals of this study was to quantify the magnitude and variability of the seasonal water use of the mesquite woodland. It was necessary to recognize the shortcomings in closure when doing this especially since the degree of closure was significantly different between the years that we compared. For our analysis we chose to follow Twine et al. (2000), who suggested that forcing closure was justified when available energy was known and errors in its measurement modest. Consequently, we scaled our latent and sensible heat fluxes to force daily closure while conserving the measured Bowen ratio. Closing the daily energy balance, rather than the half-hour balance, was preferred because energy storage was unmeasured and likely significant.

2.1.3 Mesquite ET Partitioning

Using micrometeorological techniques

The first method used to separate total mesquite ecosystem ET into overstory transpiration (the likely groundwater use) and understory ET (surface water use only) involved a micrometeorological approach[3]. We deployed two eddy covariance systems to estimate the average understory flux sensed from the tall tower. One site was located in a more closed patch near the tower, and the other was positioned in a more open patch farther away. Both understory eddy covariance sites measured ET in the same methodology and used similar equipment documented in Section 2.1.2. Understory eddy flux measurements were made during the periods June 13 – 15, July 27 - August 1, September 14 –24, 2001, and June 13 - 19, and August 13 – 18, 2002 to capture ecosystem functioning before and after the summer monsoon rains and between two years with different antecedent conditions. Energy balance closure was not forced as it was for the overstory eddy covariance measurements. The average understory evaporation was computed by: $0.7\overline{E_{MC}} + 0.3\overline{E_{MO}}$, where $\overline{E_{MC}}$ and $\overline{E_{MO}}$ are the average daily evaporation from the more closed and more open sites, respectively. This weighted average reflects the average canopy cover (~70 %) of the mesquite overstory and that the source area of the tower measurement was likely to have a similar weighting of more closed and more open patches.

Using isotopic techniques

The second method was to use the stable isotopes of water as a tracer of ET sources. With this approach our goals were to 1) develop methodology to partition ET into mesquite transpiration, understory transpiration, and soil evaporation using stable isotopes, and 2) determine the seasonal variation and totals of these evapotranspiration sources. This study will help to constrain our estimates of groundwater use at the ecosystem scale for extrapolation to the riparian corridor.

We determined the fraction of the ET flux corresponding to transpiration using an isotopic mass balance approach:

$$\mathrm{FT}\ (\%) = (\delta_{ET} - \delta_E)/(\delta_T - \delta_E)*100 \qquad (2.2)$$

[3] See Scott et al., 2003 for detailed methods and 2001 results of this study.

where δ_T is the isotopic value of water transpired by vegetation (i.e. stem xylem water), the variable δ_E is a modeled value for the signal of water undergoing evaporation from soil and δ_{ET} is the isotope signal of vapor collected within the vegetation boundary layer (Wang and Yakir, 2000). This approach was combined with the eddy covariance measurements to obtain the component fluxes in mm d^{-1}. A detailed description of the methods employed is described in Yepez et al., 2003. In this report we include estimates based on oxygen isotope ($\delta^{18}O$) variation.

ET partitioning using stable isotopes was conducted on September 22nd, 2001 and June 16th, (DOY 167), August 14th (DOY 226), September 1st and 14th (DOY 244 and 257) and October 9th (DOY 282), 2002. We estimated the seasonal trend of the contributing fluxes as follows:

Soil evaporation

The conductance of the soil surface to evaporation is high when the soil moisture content at the surface is above a certain threshold value. Below this threshold soil moisture value, conductance to evaporation is generally very low. After a rainfall event when the soil surface is wet, evaporation rate is a function of available energy (potential evapotranspiration). During the second drying phase, soil evaporation is limited by available moisture and soil physical properties. Based on the sources of ET determined from stable isotopes, we identified a threshold soil moisture value at the surface of 0.1 cm^3/cm^3, above which evaporation rate was assumed to be 35% of the daily potential evapotranspiration. This 35% value was calculated from isotope-partitioned estimates of midday average soil evaporation (mean = 5.03 mm d^{-1}) of two wet days relative to the average midday potential evapotranspiration during the same period (mean =14.36 mm d^{-1}). For days on which soil moisture was below 0.1 cm^3/cm^3 evaporation estimated from stable isotopes was 3% of potential evapotranspiration (again estimated from isotope partitioning of ET). It should be noted that all continuous soil moisture measurements were made in a single instrumented soil profile located adjacent to the Charleston Mesquite site. Given the high degree of well-documented spatial rainfall variability in the region (Goodrich et al., 1997), extrapolation of soil moisture information over the SPRNCA provides a poor representation of overall soil moisture conditions.

Understory plant transpiration

In order to account for the understory plant transpiration fraction of total ecosystem ET, we relied on the understory and overstory measurements of ET with the eddy covariance technique and independent isotope-based estimates (Yepez et al. 2003). We found that during the peak of the growing season when the understory vegetation was fully developed that it contributed 14% of the potential ET. Similarly, late in the growing season when the vegetation started to senesce understory transpiration was 8% of total potential ET (see results).

Mesquite transpiration

Weekly average tree transpiration for 2001 and 2002 was calculated by subtracting the weekly estimated understory transpiration and soil evaporation from the weekly averaged ET flux.

2.1.4 Mesquite Water Sources

Natural abundance variation in the stable isotopes of hydrogen and oxygen in water were used to partition mesquite transpiration sources into surface soil water (top 1 m of soil), deep vadose zone water (unsaturated zone moisture below 1 m), and groundwater. We focused our efforts at three mesquite sites in the SPRNCA, but the most intensive measurements were carried out at the Charleston Mesquite site. Measurements were taken during the growing seasons of 2000, 2001, and 2002.

Site descriptions

Three mesquite woodland sites (Lewis Springs, Moson, and Charleston Mesquite) were selected along the river terrace in the SPRNCA for study. These sites spanned a groundwater depth gradient from 6 to 10 m. The sites were chosen based on ease of access and the local availability of wells for stable isotope sampling. The soil at the Lewis Springs site was a clay loam in the top 50 cm underlain by sandy clay loam and loam layers. Soil at the Moson site was a loamy sand in the top 50 cm underlain by sandy loam to clay loam soils with clay content ranging from 12 to 30%. Soil at the Charleston site was a sandy loam in the top 1 m underlain by sandy loam interspersed with clay and silt-clay layers. Vegetation at Lewis Springs was a mesquite shrubland with a sacaton understory and summer annuals. Vegetation at Moson was mesquite woodland with a sacaton grass understory. Vegetation at the Charleston Mesquite site was a dense, mesquite woodland intermixed with sacaton and summer annuals.

Year 2000

Stem and soil samples were collected monthly from June through September (pre-monsoon, early-monsoon, late-monsoon, and post-monsoon). During each collection period 1-2 year old stems from the canopy were taken from 10 trees to make one composite sample. Soil samples were collected at 10-cm increment depths from the top 50 cm of the soil profile. Each soil sample was a composite of three different cores, and they were combined by volume at each depth to make one sample per depth. Stem and soil samples were placed in air-tight glass vials and immediately stored in an ice chest to minimize evaporation. Groundwater samples were collected at all ten sites in August.

Years 2001 and 2002

We again focused on these three mesquite sites in 2001 and 2002. Three trees from Lewis Springs and Moson were selected randomly from a cohort of trees in the area that were at least 6 m tall. The same trees were used for all collection periods. The seven trees chosen at the Charleston Mesquite site varied in height from 3 to 15 m. All were single-stemmed except the two smallest trees.

Soil cores were collected from underneath the canopy and in a gap near the canopy of three trees at each site. The top 50 cm of soil was collected in 10 cm increments. Therefore, a total of thirty soil samples were collected at each of the three sites at every sampling period. Groundwater samples were collected from each of the sites during each collection period.

The protocol for stem and soil collection was slightly different for 2002. Each of three cores collected on two sample dates consisted of seven samples at depths 0-10, 10-20, 20-30, 30-40, 40-50, 75, and 100 cm. Groundwater was sampled at each site during each collection period (June and August). Stems were collected from ten trees at the Charleston Mesquite site. At Lewis Springs and Moson Springs, the same three trees sampled in the summer of 2001 were sampled in 2002.

Deep soil cores were taken at Lewis Springs, Moson, and Charleston Mesquite sites in April 2001 using a truck mounted soil corer (Geoprobe). These cores sampled the entire soil profile from the surface through the capillary fringe spanning up to 10 m in depth. Deep soil cores were collected also in July 2002 using a hand auger at Lewis Springs and Moson. Soil samples were collected in 30-50 cm increments.

Isotope analysis
Water was extracted from soil and plant samples using cryogenic vacuum distillation. Water samples were then analyzed for δ^2H and $\delta^{18}O$ on an isotope ratio mass spectrometer at the Department of Geosciences Stable Isotope Facility at the University of Arizona. δ^2H and $\delta^{18}O$ from the mesquite stems, groundwater, deep vadose zone, and the top 50-100 cm of soil were used in the source partitioning models. A two-ended linear mixing model (Phillips and Gregg 2001) was used for the 2000 data and 2001 and 2002 data for Lewis Springs and Moson Springs. The three-ended mixing model was used for the data collected at the Charleston Mesquite site in 2001 and 2002. The three-ended mixing model was not used for Lewis Springs and Moson Springs sites because δ^2H values from the deep vadose zone and groundwater were too similar to precisely differentiate. Isotopic values used for the deep vadose zone and shallow soil were weighted based on matric potential of the soil layer. Any soil layer below -5 MPa was discarded because the water was assumed to be unavailable to mesquite.

Scaled estimates of water sources
Using mesquite transpiration rates from ET partitioning (sections 2.1.2 and 2.1.3 above), the transpiration fluxes of mesquite were partitioned into that from groundwater, recent precipitation, and the deep vadose zone. The fraction of tree transpiration from surface (precipitation) moisture was highly dependent on soil moisture content at the 20-100 cm depth increment. The linear relationship between volumetric soil moisture content between 20-100 cm depth and the fraction of moisture uptake from this layer determined by isotope methods was highly significant (fraction from surface = 14.8*(soil moisture content)-0.68; $r^2 = 0.93$, $P < 0.01$). This line of regression was used to find the precipitation use for each week from May 1 to October 21 of 2001 and 2002 (DOY 121-321). ET fluxes derived from groundwater and the deep vadose zone were calculated using the proportions from the three-ended isotope mixing model. The remaining water that was not precipitation use was divided into groundwater and deep vadose zone based on their calculated proportions from isotope measurements. From this, estimates of weekly and annual growing season transpiration from groundwater by the mesquite ecosystem at the Charleston Mesquite site were made.

2.2 Mesquite Shrubland and Sacaton Grassland

2.2.1 Site Description

Established in mid-2002 through a new collaborative project with Prof. Travis Huxman (U. of Arizona and SAHRA), the Lewis Springs sacaton and mesquite study sites are located close to each other on the east side of the San Pedro River at an elevation of 1230 m, approximately 12 km east of Sierra Vista, Arizona, near the Lewis Springs USGS Transect (Fig. 2-1). The micrometeorological tower at the Lewis Springs Sacaton Site (LSS) lies in the center of a low alluvial terrace bordering the river. The tower is surrounded by a lush growth of sacaton grass (*Sporobolus wrightii*) roughly 200 m east /west and 800 - 1000 m north/south. The canopy height is about 1 m, and average canopy density is ~ 70 %. The mean depth to groundwater in a co-located piezometer is ~ 2.8 m. The measured Leaf Area Index (LAI) (LI-2000, LI-COR, Inc., Lincoln, NE) ranged from an average (n = 40) of ~1.0, prior to greenup, ~1.5 during the pre-monsoon season, and ~2.5 during and after the monsoon season. The flux tower at the Lewis Springs Mesquite Site (LSM) lies immediately to the northeast of LSS in a moderately dense shrubland of velvet mesquite (*Prosopis velutina*), roughly 500 m east/west by 500 m north/south. The mesquite canopy density is estimated to be 60% with an average tree height of 3 – 4 m. The depth to groundwater is ~ 7 m, and the LAI ranges from about 0.3 (prior to leaf flush) to a peak of 0.6 during the monsoon.

2.2.2 Metflux Instrumentation

The basic meteorological, soil moisture and eddy covariance instrumentation and methods at both LSS and LSM mirrors that of the Charleston Mesquite Site (CM, Section 2.1). The heights of the flux instrumentation were 2.8 m at LSS and 6.5 m at LSM. Energy balance closure information is summarized in Table 2-2. Using the same rationale given in Section 2.1, both latent and sensible heat fluxes were forced to close the daily energy balance while conserving the measured Bowen ratio.

Both sites lie in areas with more heterogeneous vegetation density and less extensive vegetation patches than the CM site. This potentially complicates the interpretation of the measured fluxes. For this report, we have not fully resolved what filtering of the fluxes based on wind speed and direction might be needed to insure that the measured fluxes were indeed representative of the vegetation type of interest. Thus, we caution that these results may be revised following future analysis. Likewise for all three eddy covariance sites, the issue regarding how to interpret the lack of closure has not been resolved within the scientific community. We chose to follow the work of Twine et al. (2000) (see discussion of rationale in Section 2.1.2) for this report and forced closure on the daily energy balance, increasing the measured ET by as much as 23%. By doing this, we implicitly assumed that the measured available energy was more accurate than the measured turbulent heat fluxes, which may or may not have been the case.

Table 2-2. Ordinary linear regression coefficients for energy balance closure at the LSS and LSM sites in 2003

	n	Slope	Intercept	R^2
30-min values				
LSS	12369	0.95	-27.7	0.95
LSM	12409	0.82	-0.9	0.90
Daily means[b]				
LSS	276	0.77	-2.5	0.80
LSM	278	0.80	2.5	0.85

[b] for days with at least 24 half-hourly values of all energy balance components.

2.3 Cottonwood

2.3.1 Site Descriptions

The study sites used for cottonwood sapflow measurements were the Boquillas-UA and Lewis Springs sites (Fig. 2-1). Four cottonwood trees were monitored at each site (intermittent reach, Boquillas-UA site, average GW depth = 3.3 m; perennial reach, Lewis Springs site, GW depth = 1.6 m) of the SPRNCA.

2.3.2 Sapflow Instrumentation

Basal sap flow measurements
Sap flow of each tree was measured using a thermal dissipation probe (TDP-30 and TDP-80, Dynamax, Inc., Houston, Texas). Sets of these Granier-type probes were implanted on the north and south side of each tree at 1.75 m above the ground. Sap flow was measured simultaneously on four trees per site from April to November 2003 using a data logger (Campbell 10x datalogger). Plastic putty was installed around the needles for water protection and foam quarter-spheres were tightly secured on both sides of the needles to protect the wire from bending stress and to provide thermal insulation to the needles. Reflective bubble wrap was also installed around the tree for additional insulation.

The Granier method was used to calculate a dimensional parameter (K) as:

$$K = \frac{(\partial T_m - \partial T)}{\partial T} \tag{2.3}$$

where ∂T is the measured difference in temperature between the heated needle, referenced to the lower non-heated needle; ∂T_m is the value of ∂T when there is no sap flow. Average sap flow velocity [V, cm s^{-1}] is calculated as:

$$V = 0.0119 * K^{1.231} \tag{2.4}$$

Sap flow velocity was then converted to sap flow rate [J_s, cm^3 h^{-1} or g cm-^{2} h^{-1}] using this equation:

$$J_s = Area\ of\ sapwood\ cm^2 * V * 3600\ s/h \qquad (2.5)$$

Scaling

Cottonwood stand transpiration (E, mm day^{-1}) was scaled based on individual tree sap flow, total sapwood area and crown area of the cluster (Wullschleger 1999). Sapwood area was determined from increment cores taken as close as possible to the probe insertions on each side of the tree. Sapwood was identified from heartwood by color change from lightly colored to darkly colored and water saturated heartwood. Total canopy area (A_L), sapwood area (A_S), A_L:A_S (Table 2-3) and diameter (diameter at breast height at 1.5 m) of all the trees in the cluster were measured at both sites. The sapwood area-to-diameter relationship was used to estimate the total sapwood area of all the trees in the cluster (Schaeffer et al. 2000).

Table 2-3. Structural characteristics of cottonwood clusters at Lewis Spring and Boquillas sites along the San Pedro River in Southeastern Arizona.

Site	Stems	Canopy Area* (m^2)	Sapwood Area (cm^2)	A_L:A_S ** (m^2 cm^{-2})
Lewis Spring	9	421	7175	0.31 ± 0.04 a
Boquillas	10	1037	12232	0.21 ± 0.02 b

*Canopy area refers to the planar area of the canopy as seen from aerial photographs
** Leaf area: sapwood area ratio, significant at P=0.10

For trees instrumented with TDP-80, sap flow rate per tree was scaled based on the sapwood area that covers the position of the two thermocouples per probe. The total water use for the two thermocouple positions were then added and then divided by the total sapwood area of the tree to get J_s, the average sapflow rate per unit sapwood area [g cm^{-2} h^{-1}], for each instrumented tree. J_s from the north and south side of each tree was averaged to get $\hat{J}_s$. $\hat{J}_s$ from each tree was then averaged for all the instrumented trees in the cluster to get the $\overline{J_s}$ which was then multiplied with the total sapwood area of all the trees in the cluster to get the total water use (kg d^{-1}). Total water use of the entire cottonwood stand was divided by the projected canopy area (m^2) to determine total water loss or transpiration of the entire stand, E (kg m^{-2} d^{-1} or mm d^{-1}). The projected canopy area of the clusters was estimated digitally using aerial photographs.

Leaf area index, meteorological, and groundwater depth measurements

Leaf area index (LAI) was measured using a plant canopy analyzer (LAI 2000, LICOR, Lincoln, NE) in October 2003. LAI readings were taken from 4 cardinal directions around the base of each tree within the cluster. Meteorological data were measured at nearby towers located at the Charleston Mesquite and Lewis Springs West sites. Air temperature, relative humidity, solar radiation, wind speed, air pressure and precipitation were measured from these sites. Depth to groundwater (GW) was measured manually on a weekly basis at the Boquillas-UA site. US Geological Survey provided data on water table depth at the Lewis Springs site.

2.4 Seep Willow Transpiration and Open Water Evaporation

2.4.1 Site Descriptions

The Lewis Springs study site is located approximately 10 km east of Sierra Vista, Arizona (Fig. 2-1) at 1240 m elevation on the east of the San Pedro River. This site is at the USGS Transect, just north of the AZ Hwy 90 bridge crossing within the active floodplain of the river. Along the primary and secondary channels of the river, Fremont cottonwood (*Populus fremontii*) and Gooding willow (*Salix gooddingii*) are the main overstory species with seep willow (*Baccharis salicifolia*) as the dominant understory species. A broad floodplain is situated between the primary and secondary channels and is covered primarily with Johnson grass (*Sorghum halepense*) and sacaton grass (*Sporobolus wrightii*) along with sparse patches of cottonwood trees and seep willow shrubs. During the 2002 and 2003 measurement periods, there were several flood events that inundated the site. The depth to groundwater in a nearby USGS piezometer ranged from 1 to 1.6 m.

2.4.2 Sapflow and Evaporation Instrumentation

Sapflow Study
Two patches of seep willow shrubs were selected for this study. One patch was situated under a more sheltered cottonwood canopy, and the other patch was located in an open area with no immediate overstory vegetation present. Transpiration was estimated using the stem heat balance sap flow technique (Sakuratani, 1981). In this approach, plant sap flow is determined by application of a constant external heat source to the shrub stem while measuring the axial and radial heat losses from the stem. The amount of heat lost due to convection, and transport of heat with the movement of sap, can be calculated.

The sap flow sensor consists of three basic components (Fig. 2-2): 1) a heat source wrapped around a section of the plant stem; 2) three differentially wired thermocouples, with the reference thermocouple at the center of the heat source, and the remaining thermocouples 15 mm upstream and downstream from the heat source to measure axial heat loss; and 3) a thermopile wrapped around the stem at the heat source to measure radial heat loss. Sensors were insulated with two layers of foam insulation material and one layer of Bubble Pack Insulation with reflective backing wrapped to reduce any influence of thermal perturbations from the surrounding climate conditions. All sap flow sensors were measured using a CR-10 datalogger (Campbell Scientific, Inc., Logan, UT) powered by a 12-volt battery. Data was logged every 30 min for all sensors and was collected every 7-10 days using a laptop PC.

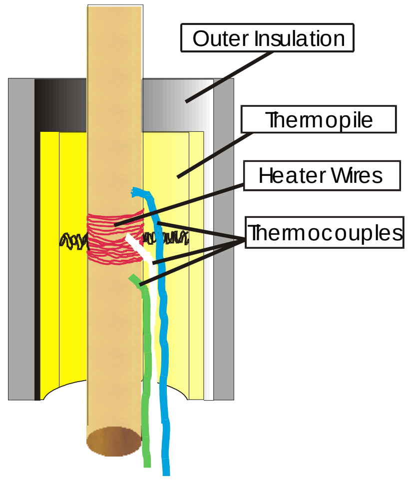

Figure 2-2. Sap flow sensor unit

Once power is supplied to the sensor system, the following equations are applied to the raw data to separate the heat inputs and calculate stem sap flow:

$$Q_H - Q_f - Q_{up} - Q_{dn} - Q_{rad} = 0 \qquad (2.6)$$

where Q_H represents heat input; Q_f refers to the convective heat carried by sap flow; Q_{up} and Q_{dn} apply to the heat conducted upstream and downstream through plant stem, and Q_{rad} is radial heat loss away from the stem and heat source. Units for all these components are J s^{-1}. The components of Eq. 2.6 can be calculated as follows:

$$Q_H = V_{in}^2 / R_H \qquad (2.7)$$

where V_{in} is the voltage supplied to the heater and R_H is the corresponding heater resistance (Ω). Up and down stem conduction heat components can be determined from

$$Q_{up} = 0.42\ (\pi\ d^2/4)(\delta T_{up}/L_{up}) \qquad (2.8)$$
$$Q_{dn} = 0.42\ (\pi\ d^2/4)(\delta T_{dn}/L_{dn}) \qquad (2.9)$$

Where 0.42 (J s^{-1} m^{-1} $°C^{-1}$) is the approximate thermal conductivity of woody plant stems, d is the plant stem diameter (m) at the heater source, δT_{up} and δT_{dn} are the temperature differences between the heater and thermocouples located upstream and downstream (˚C), and L_{up} and L_{dn} is the distances from heaters edge to the upstream and downstream thermocouples. A radial conductance (K_{rad}) must be calculated during a time of zero or near zero flow (early morning hours) in order to determine radial heat loss (Q_{rad}):

$$K_{rad} = (Q_H - Q_{up} - Q_{dn}) / \delta T_{rad} \qquad (2.10)$$

Where K_{rad} units are J s^{-1}°C^{-1} and δT_{rad} refers to temperature difference between the heat source and the outside of the thermopile (˚C). Once K_{rad} values have been calculated, radial heat loss (Q_{rad}) can then be determined:

$$Q_{rad} = K_{rad} * \delta T_{rad} \quad (2.11)$$

Convective heat carried by sap flow (Q_f) can then be determined by subtracting all the other elements of Eq. 2.6.

$$Q_f = Q_H - Q_{up} - Q_{dn} - Q_{rad} \quad (2.12)$$

The convective heat loss due to sap flow (Q_f) is then converted into an equivalent mass flow (S)

$$S = 3600Q_f / 4.19 * \delta T_{up-dn} \quad (2.13)$$

where units of S are in g h^{-1}, 4.19 refers to the specific heat of liquid water ($J^{-1}g^{-1}{}^{\circ}C^{-1}$), 3600 are the number of seconds in one hour, and δT_{up-dn} refers to the difference in temperature between upstream and downstream thermocouples.

Pan Evaporation Study

In order to estimate the amount of evaporation that occurs directly from the river, an open water evaporation study was carried out. Twelve eight-inch square aluminum pans and twelve standard rain gauges were used in the open water evaporation study. Both pans and gauges were placed along the river edge, within primary and secondary channels and within the floodplain area in order to better quantify the evaporation in the heterogeneous microclimate. Each pan was filled with water and set into the soil so that the rim was level with the ground surface. Both the placement and the pans' small size was chosen so as to minimize "oasis-effects" that can occur with pan evaporation studies. This study was conduced over a six-day period (June 25 to July 2, 2003) during the pre-monsoon season. At the onset of the study, each pan was filled with 700 ml of water. The volume of water of each pan was measured with the use of a graduated cylinder every twenty-four hours for the period, and then refilled back to 700 ml. Rain gauges were monitored each day of the measurement period. The volume of water evaporated from each pan was divided by the surface area of the pan and the amount of time elapsed between measurements to compute an evaporation rate. We compared the mean evaporation rate to a standardized or reference evaporation, ET_o, which was computed using the AZMET standard (Brown, 1889; http://ag.arizona.edu/azmet/et2.htm) and met data from the nearby Lewis Springs Met Site (see Appendix 2).

2.5 Total SPRNCA Water Use

Goodrich et al. (2000) made the most recent estimates of riparian groundwater use along the San Pedro using estimates of vegetation area that were made from a 1997 *pixel-based* vegetation classification (hereafter referred to as VEG97). In the map, each 3 x 3 m pixel is classified as a particular vegetation cover. From aerial photography made in 2000 and field data collected in 2001, the U.S. Army Corp of Engineers produced a new *polygon-based*, GIS vegetation cover map (VEG00), where continuous stands of vegetation were delineated and given various attributes such as vegetation alliance, polygon area, total area of vegetation cover, area of dominant vegetation cover, etc. It includes 33 different vegetation communities, open water, and urban lands (See Fig. 2-3 as an example).

Several differences between the two maps required that various GIS manipulations be conducted so the VEG00 map could be used for water use analysis and in the ET Tool. The VEG00 map extent matched the boundaries of the SPRNCA, while the VEG97 map was created for the San Pedro River riparian corridor from Palominas to north of St. David (see Goodrich et al. 2000). To use the VEG00 map for this project it was first clipped to the same extent as the VEG97 map. Since VEG97 did not cover the entire SPRNCA, the riparian corridor outline for VEG00 was extended with the use of a 1 m digital elevation model (DEM) derived from LiDAR data (2003), aerial photographs, and the vegetation classes in the map itself.

An additional vegetation analysis was conducted to delineate the riparian area that was within 3 m of the river bottom (thalweg) or stage, whichever was highest. Standard ArcInfo GIS functions were used with the 1 m DEM to determine the minimum elevation at the river for each horizontal row of grid cells along the entire river length within the SPRNCA. This elevation value was then used to identify all grid cells along that horizontal row of grid cells that were within 3 m of that elevation. Limitations to this method occurred when the river trended east-west and intersected the horizontal row more than once. In those instances manual interpretation was used to identify the boundary.

The conversion from a pixel- to a polygon-based coverage made the task of computing total vegetation areas for the relevant land cover types more difficult. For the new map, VEG00, both the polygon area and the percent area that is covered by the vegetation of interest were needed to estimate the total area of groundwater-using vegetation. The basic classification in VEG00 has five ranges for the vegetation percent cover. They are: 1 – 10, 11 – 25, 26 – 60, 61 – 80, and 81 – 100 %. This range is quite coarse for calculating the total area covered by a specific vegetation type and produces uncertainty in the new estimates of vegetation groundwater use. To reduce this uncertainty, the map provides the vegetation percent cover estimated to the nearest 5 % for the mesquite or cottonwood polygons classified as a woodland or forest, defined as those patches dominated by mesquite or cottonwood/willow with greater than 60 % cover.

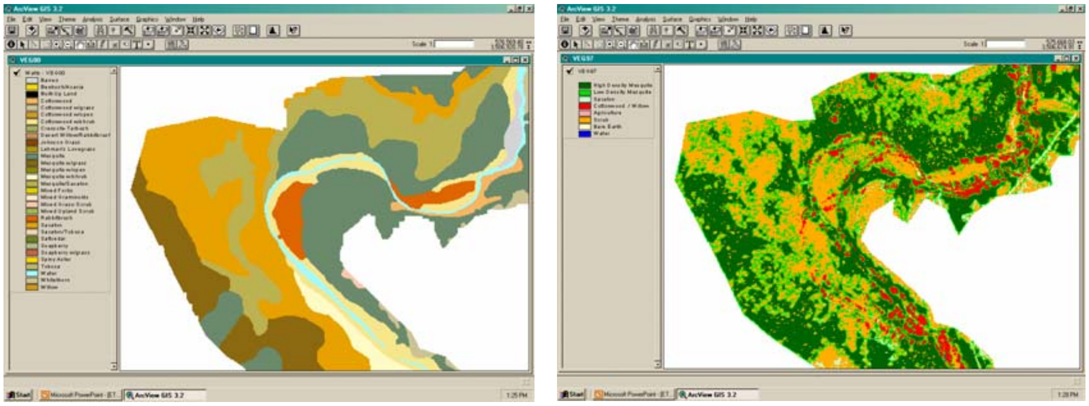

Figure 2-3. The vegetation distribution for an example reach of the SPRNCA as given by the polygon-based VEG00 (left) and the pixel-based VEG97 (right) maps.

Unfortunately, there are still many polygons not classified as woodland or forest that contain vegetation that uses groundwater (e.g., mesquite areas with less than 60 % cover, sacaton grasslands, etc.). We incorporated this uncertainty into the new SPRNCA water use estimates by computing a range (minimum to maximum amount) of area for each functional vegetation group. Then, the total vegetation area was calculated by summing up, over all polygons of a certain plant functional group, the product of the polygon area and the minimum, median, and maximum percent cover, or, if the more accurate percent cover was available, then this was used instead.

3 Ecosystem Studies Results

3.1 Mesquite Woodland

3.1.1 Mesquite Woodland Water Use

ARS monitored evapotranspiration fluxes above the Charleston Mesquite (CM) Site during the 2001, 2002 and 2003 growing seasons. All three growing seasons were preceded by dry winters with little precipitation (Fig. 3-1). The winter prior to the 2001 growing season was also quite dry, yet there was still a lot of carryover soil moisture from the large amount of rainfall that fell in October, 2000.

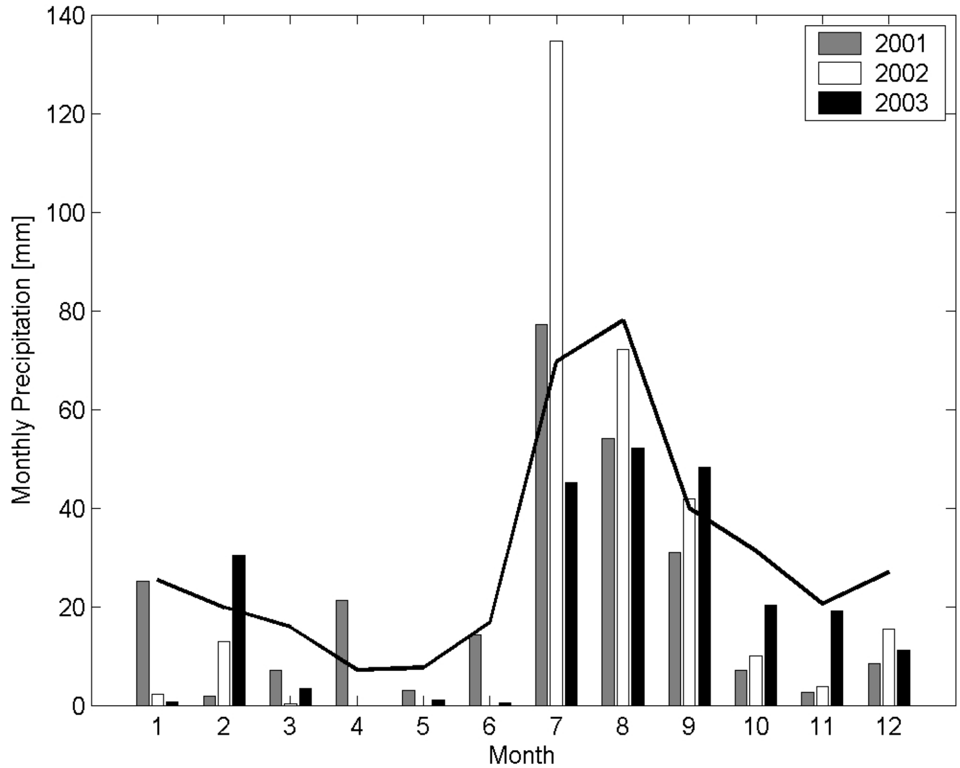

Figure 3-1. 2001-2003 total monthly precipitation at the Charleston Mesquite Site. For comparison purposes, the line represents 1971 - 2000 monthly average precipitation from Tombstone, AZ.

By continuous monitoring of the groundwater levels and the ecosystem evapotranspiration, we were able to determine that the mesquites were using groundwater. The spring 2002 green-up provides one of the many examples of evidence for this (Fig. 3-2). The winter and spring of 2002 were very dry and surface soils were also very dry, but despite this drought, the trees leafed out and began to take up carbon dioxide (negative NEE) and lose water vapor in mid-May. At this same time, groundwater levels began to drop and a regular pattern of diurnal groundwater drawdown (with groundwater closer to the surface in the early morning and farther from the surface at sundown) became established, providing clear evidence of a direct link between tree water use and groundwater fluctuations. This pattern of diurnal groundwater fluctuations due to mesquite uptake continued throughout most of growing seasons, but the diurnal fluctuations ceased during limited monsoon periods when surface soils were very wet (discussed below). We present more information about the tree's water source in the following subsections.

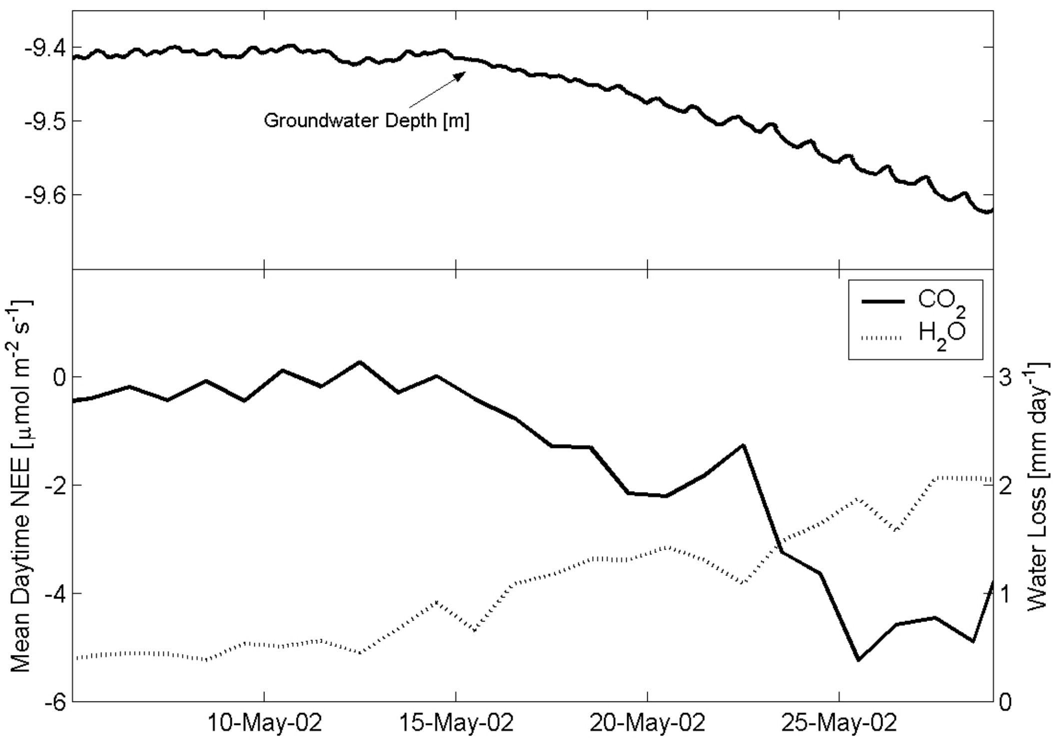

Figure 3-2. Groundwater depth below surface (upper panel), average daytime net ecosystem exchange of CO_2 (NEE, solid line), and daily average evapotranspiration (dotted line) in May of 2002. Regular diurnal fluctuations in the water table were induced by the water uptake of tree roots. *(Figure from Scott et al., 2004).*

Measured mid-canopy air temperature indicates that the last freezes of spring occurred on 6 May 2001, 22 May 2002, and 11 May 2003. The first freezes of fall occurred on 13 October 2001, 4 October 2002, and 27 October 2003 (data not shown). These freeze events effectively constrained the mesquite growing season and hence much of vegetation water use in the riparian corridor. The mesquite trees leafed out in the spring around the time of the last spring freeze. This was followed by a substantial increase in ET, beginning around mid-May of both years (DOY 130 - 145, Fig. 3-3). Conversely, in fall, ET dropped quickly as the mesquite trees began to senesce in late October (~ DOY 290). The freeze intolerance of mesquite is consistent with a previous study of mesquite by Scott et al. (2000). It is important to note that temperatures in the riparian corridor were often quite different from those measured above the riparian bottomland on the valley floor (Appendix 2). While maximum daytime temperatures agreed well, the minimum nightly temperatures were generally 5 -10 °C lower in the riparian corridor, except in the more humid monsoon season when the difference was less. Because the water use of the mesquite trees (and likely other riparian tree species) was constrained by the frost-free period (typically about 150 days), models of riparian evapotranspiration will require knowledge of air temperature within the riparian corridor itself, or at least estimates based on a known relationship between temperature in the riparian corridor and that measured elsewhere.

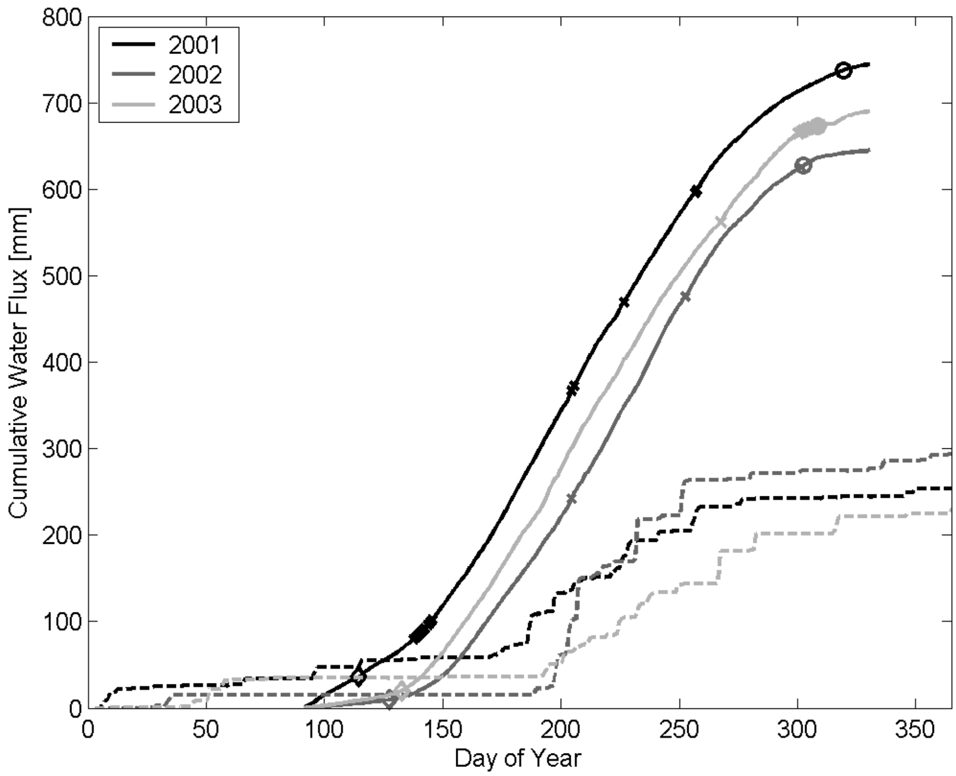

Figure 3-3. Cumulative fluxes of precipitation (dashed lines) and evapotranspiration (solid lines) for 2001, 2002, and 2003 at the mesquite woodland site. Interpolated values are indicated with an "x". The last freeze of spring is indicated by a diamond and the first freeze of autumn is indicated by a circle. Note: only evapotranspiration data from April 1st to November 28th of each year are shown since 2001 data were limited to this time period.

In this semiarid environment, the availability of near-surface soil moisture for understory plants is closely linked with recent rainfall (Fig. 3-4a). Not surprisingly, it takes longer for the near-surface soil profile to dry after winter rainfall due to the lack of plant uptake and decreased evaporative demand. In 2001, the effect of precipitation was rarely seen at 50 cm depth, indicating that there was very little deep infiltration during much of the year and that most summer precipitation was either quickly evaporated or transpired. However, after the larger storms during the 2002 monsoon, moisture moved further down the soil profile, past 50 cm depth, although even then there was only a slight 2% increase in soil moisture at 100 cm depth (not shown). Infiltration in 2003 was very similar to 2002 though the wetting of the near-surface soils was shallower due to less intense monsoon rains. The entire root zone profile was substantially wetter in the spring of 2001, probably because there were anomalous rains totaling 125 mm in October 2000, though the origin of this soil moisture is not certain because soil moisture probes were not installed until March 2001. Annual precipitation totals were 253 mm in 2001, 293 mm in 2002 and 232 mm in 2003, respectively, while the monsoon rainfall, i.e. the cumulative total between the mid-summer onset of precipitation and the end of September, were 177 mm in 2001, 248 mm in 2002, and 146 mm in 2003. All of the study years had below average precipitation, but the typical pre-monsoon “drought” was especially long and severe in 2002 (Fig 3-1).

The depth to groundwater fluctuated in response to both local and more regional forcing (Fig. 3-4b). All years showed the influence of mesquite activity on water table depth with increasing depths and regular diurnal water table fluctuations beginning in mid-May in response to mesquite leaf flush, and water level recovery and no diurnal fluctuations after mesquite senescence (~late October). The diurnal fluctuations were more muted in 2003 probably because the well transducer had developed a film that damped the transducer sensitivity. The mid-summer monsoon had a complex influence on the water levels (~July - September). During this time, it is likely that water levels in this piezometer responded to both large floods passing through the nearby river channel and the mesquite supplementing water uptake with lateral, surface roots when and where surface water and nutrients were available.

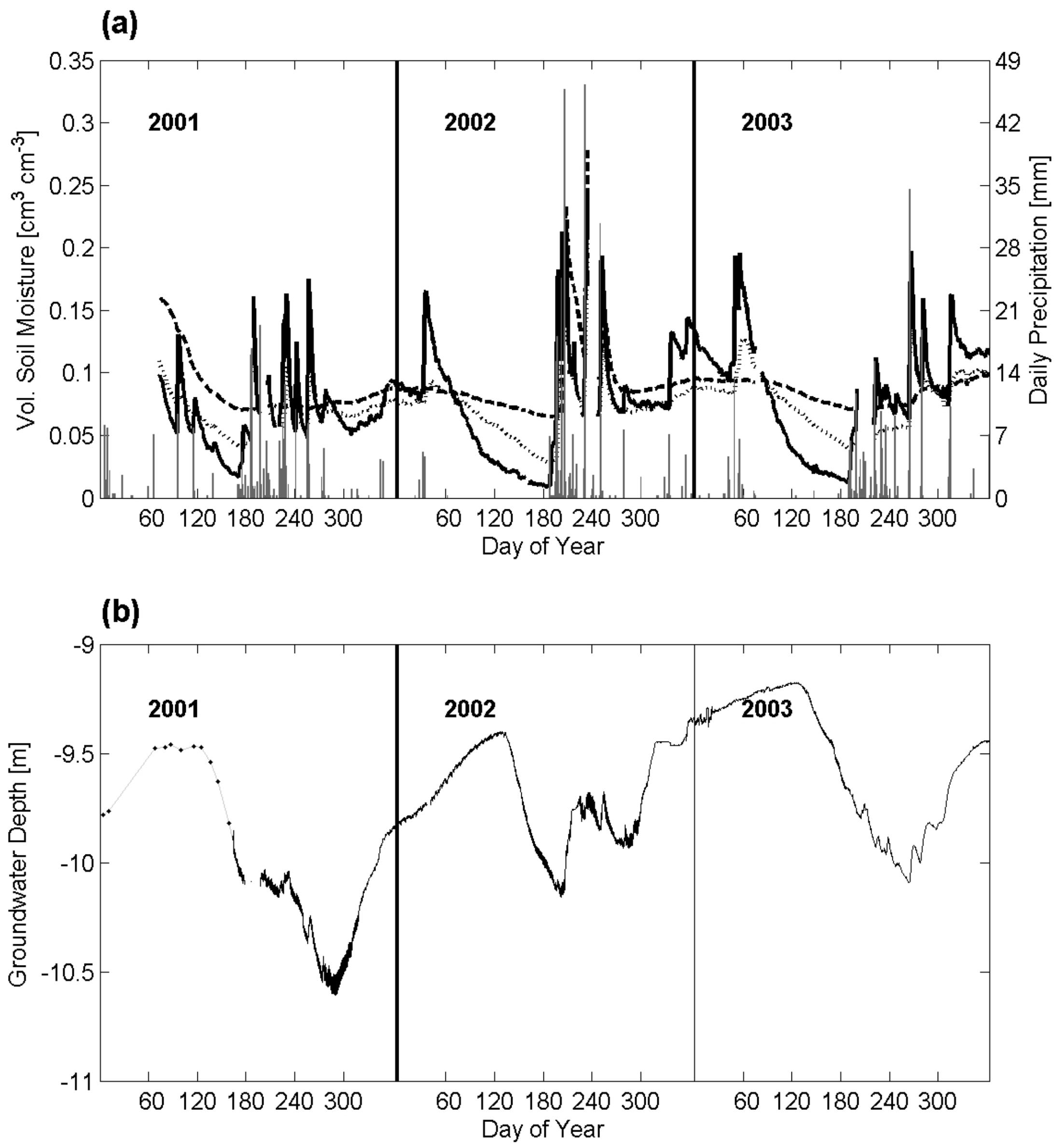

Figure 3-4. (a) Daily precipitation (gray bars) with volumetric soil moisture at 5 cm (solid line), 25 cm (dotted), and 50 cm depths (dashed). (b) Groundwater depth below surface, prior to DOY 166, 2001, measurements were taken manually.

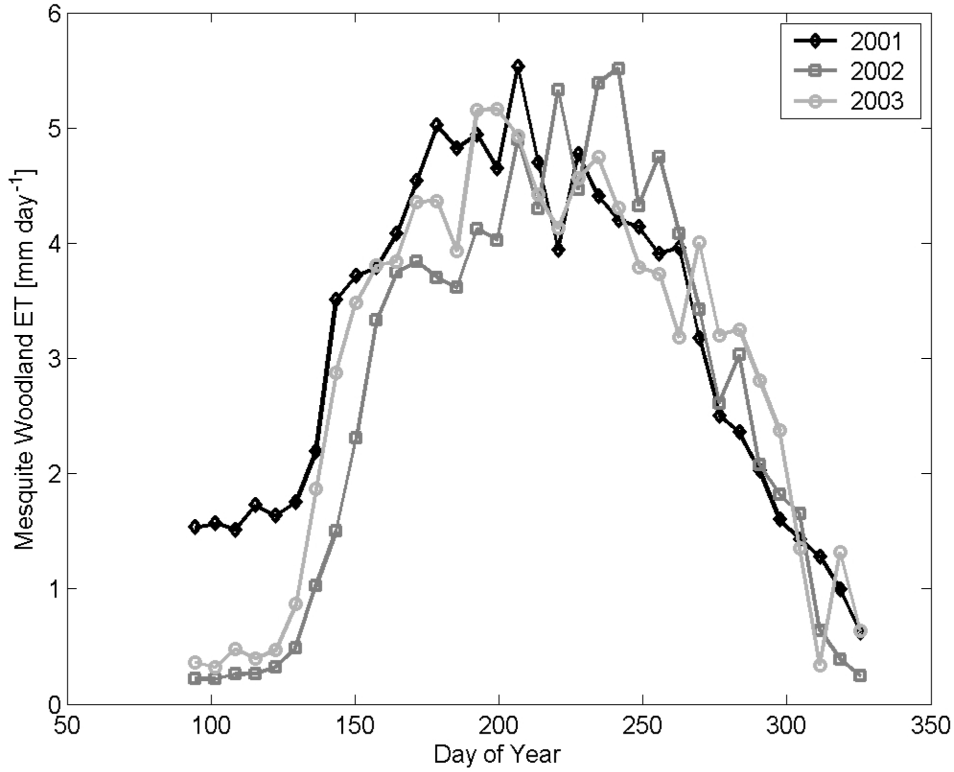

Figure 3-5. Average weekly mesquite woodland evapotranspiration for 2001, 2002, and 2003.

While much of the variability of total ET can be attributed to when the growing season began and ended, monsoon rainfall and antecedent soil moisture conditions also appeared to influence ecosystem water use. In 2001, the ET was substantially higher prior to mesquite leafout due to understory ET (mainly sacaton transpiration) that was fueled by near-surface soil moisture (Figure 3-5.) Also, the pre-monsoon dry period was considerably shorter due to an early arrival of monsoon rains. The site experienced dry winters prior to 2002 and 2003, and consequently the ET was low prior to mesquite leaf flush (~DOY 130). After this, there was a considerably faster increase in ET and higher pre-monsoon ET in 2003 relative to 2002. Thus, the trees in 2002 appeared to be more drought stressed or possibly damaged by a late frost-- resulting in the lowest seasonal ET of the study, despite the fact that the trees had access to groundwater and the near-surface soil moisture was nearly identical to 2003 conditions.

We speculate that the more stressed conditions of the trees in 2002 were a result of drier meteorological conditions (i.e., higher vapor pressure deficits) which Scott et al. (2004) have shown to be related to stomatal regulation. Additionally, it could have been due to unknown consequences of hydraulic redistribution of previous rainfall by the mesquite trees themselves. Hultine et al. (in press) discovered that mesquite at this site have the ability to redistribute near-surface soil moisture to the deeper vadose zone throughout the entire year (Fig. 3-6). Moisture redistribution followed the moisture potential gradient with upward “lifting” of deep vadose zone moisture or groundwater during the dry season and downward descent of precipitation during times of abundant surface moisture. The antecedent monsoon and winter rains prior to the 2003 growing season were higher implying that more of this moisture may have been redistributed to deeper layers in the vadose zone that later improved mesquite functioning during the pre-monsoon drought period.

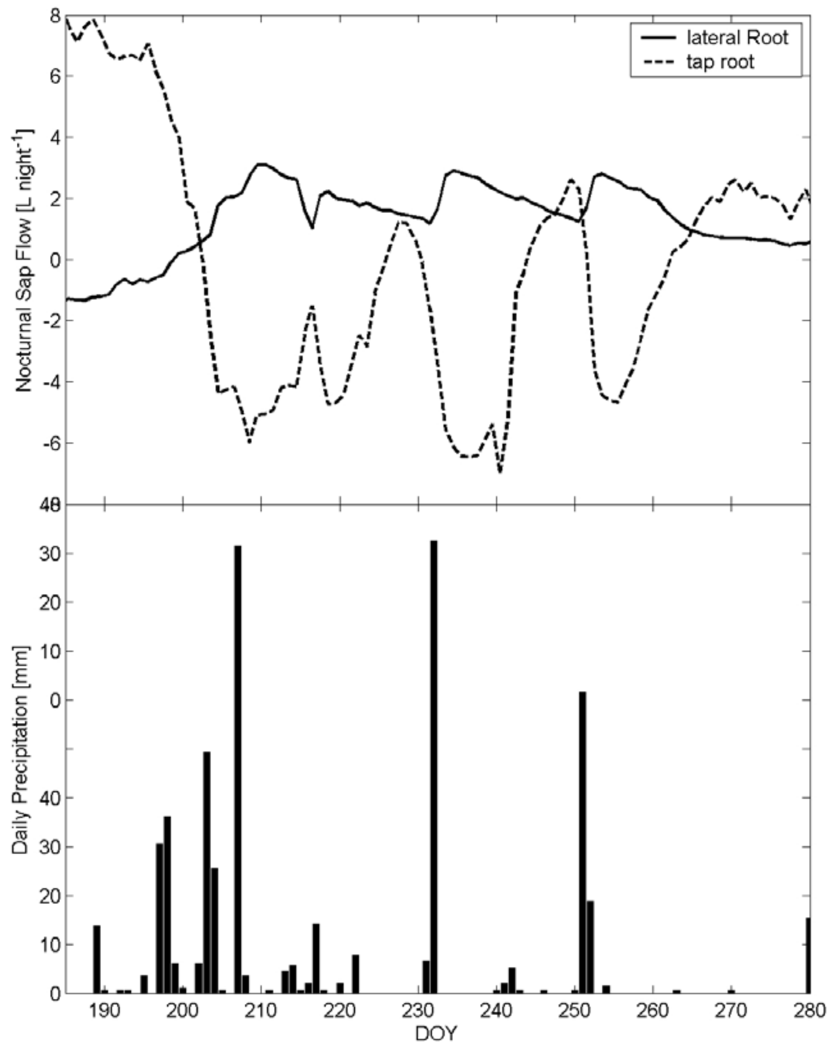

Figure 3-6. (upper panel) Total nighttime sap flow of the taproot, and lateral root of a mesquite tree at the CM site, calculated from half hourly measurements between 8 pm and 5:30 a.m. Negative values represent reverse flow (i.e. flow away from the crown). There was a significant inverse correlation between nocturnal sap flow in the taproot and nocturnal sap flow in the lateral root (R^2 = 0.85, P < 0.0001). (lower panel) Daily precipitation totals at the field site during the study. ***Adapted from Fig. 5, Hultine et al., in press.***

One method to estimate entire growing season groundwater use from these ET measurements is to use the water balance equation:

$$Q_t = ET - (P - \Delta S) \tag{3.1}$$

where Q_t is groundwater use, ET is evapotranspiration, P is precipitation, and ΔS is the change of soil moisture in the top 1 m of soil. At the site, runoff was negligible and we assumed that there were only small changes in soil moisture deeper than 1 m. Thus, Q_t, if positive, is the ET in excess of precipitation and soil moisture storage. We assumed that all of the excess moisture was derived from groundwater. In light of the discovery of hydraulic redistribution of mesquite (Hultine et al., in press) this was an overly simplistic view, but we did not have a method for computing the change in storage in the deep (> 1 m below the surface) vadose zone. Lastly, we computed the amount of groundwater used on a per unit mesquite area, $Q_{mesquite}$, (rather than per unit ecosystem area) by dividing Q_t by the percent cover of mesquite found at the site.

Table 3-1 lists the components of the 2001, 2002 and 2003 mesquite woodland water balance along with the measurements made in 1997 (Scott et al. 2000). Goodrich et al. (2000) used the 1997 measurements for their consumptive use estimates. The aerial coverages of mesquite at the compared sites are estimated to be 0.5 and 0.74 for 1997 and 2001-2003, respectively. While the 1997 measurements were at a site that was considerably less dense, these differences were not sufficient to explain the much greater groundwater use of the woodland site. The 2001 – 2003 CM Site had much larger and more mature trees. The trees at the 1997 site, being less developed, were arguably less adept at tapping the deep groundwater source. (The water-table depth at both sites was ~ 10 m).

Table 3-1. Mesquite Growing Season Water Balance (May 1 – Nov 27). Units are in millimeters. See above for term definitions.

	1997	2001	2002	2003
ET	330	694	638	676
$P - \Delta S$	173	206	244	166
Q_t	157	488	394	510
$Q_{mesquite}$	314	659	532	689

The new 2001-2003 mesquite measurements also show that the mesquite groundwater use varied considerably between the years. In 2002, much drier and hotter conditions prevailed in the first two months of the growing season prior to the onset of the summer rains. The trees showed considerably more stress (Scott et al., 2004), which resulted in less groundwater use. Above we speculated on some possible reasons for this variability. Also the monsoon rainfall was more abundant in 2002 and likely offset some of its groundwater use.

In Section 3.2, we compare the functioning of this mature mesquite woodland site with a less-dense and smaller mesquite shrubland site to determine how representative these measurements might be of other mesquite ecosystems along the San Pedro.

3.1.2 Mesquite ET partitioning

Using micrometeorological techniques

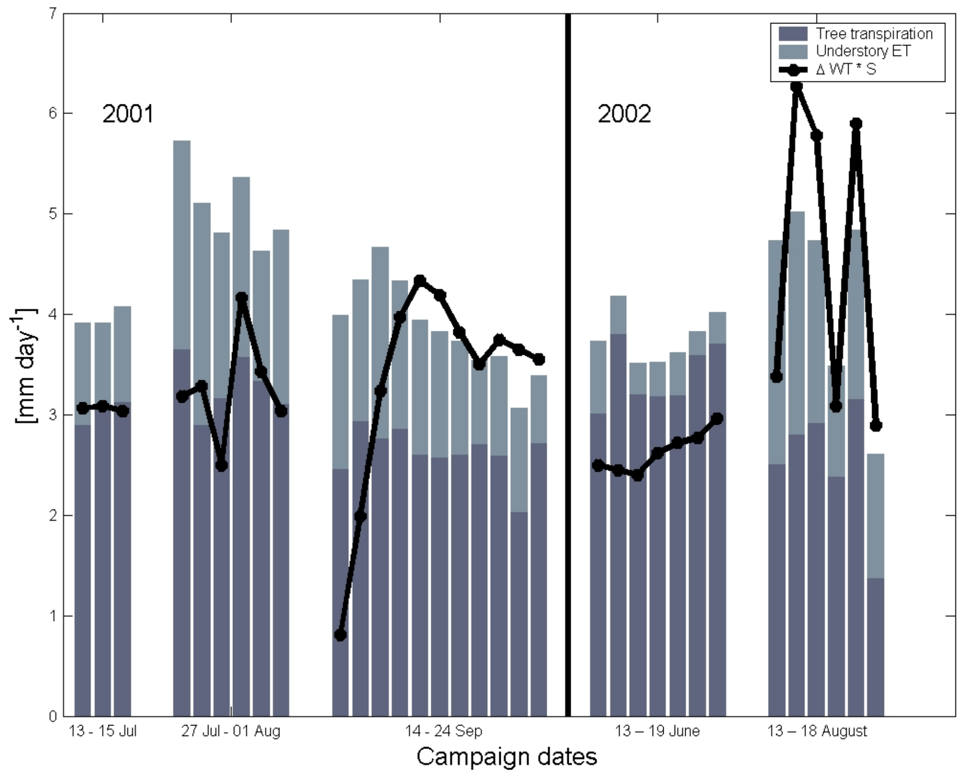

Figure 3-7. Total daily evaporation from the mesquite ecosystem (total bar height) and its partitioning into overstory/understory sources. Additionally, the product of the maximum daily water table fluctuation (as measured in a local piezometer) and an estimated specific yield of 0.08 are shown. All units in mm day-1.

The understory/overstory ET data collected in 2001 and 2002 reveal that overstory water use (i.e., mainly tree transpiration) was nearly constant during the pre-monsoon to monsoon periods (Fig. 3-7). The difference in total ecosystem water use throughout the growing season was principally due to changes in the understory evapotranspiration, while the overstory water use did not appear to increase despite the changes in near-surface soil moisture. The trees certainly had access to a source of deeper vadose zone water during the pre-monsoon campaigns and the tree transpiration did not change significantly when near-surface soil moisture increased. Although it is possible that the trees changed from a deep to a shallow moisture source during the monsoon, this is unlikely because it would require a significant investment of resources to entirely alter their hydraulic architecture. Furthermore, a strong correlation between daily tree water use and daily water table fluctuation was found. This agreement changed little from the pre-monsoon to the monsoon campaigns. In fact, the daily water table drawdown increased somewhat in the September 2001 and August 2002 campaigns – providing additional evidence that mesquites' main water source remained groundwater. The constant of proportionality between the water table fluctuations and overstory evaporation also changed during the post-monsoon campaign, perhaps due to the lower water levels in the piezometer. At a lower water table elevation, a portion of the aquifer with different hydraulic properties might have been influencing water levels. Unfortunately, we did not have a way to verify this suggestion.

Isotope results
Our data indicates that the relative contributions of E and T to the total ET flux were highly responsive to inputs of precipitation, but transpiration was the dominant source of water loss through most of the growing season.

Late in the growing season of 2001 (September 22nd) total ET was 70% from mesquite transpiration, 15% from transpiration by the understory plants and 15% from soil evaporation. Combining these data with estimates of ET from eddy covariance revealed that of the 3.5 mm d^{-1} evapotranspiration, 2.5 mm d^{-1} was from transpiration by mesquite, 0.5 mm d^{-1} from the understory plants and 0.5 mm d^{-1} from soil surface evaporation (Figure 3-8a; Yepez et al., 2003).

The fraction of total ET attributed to transpiration in 2002 varied from around 100% during dry periods to about 40% following large precipitation events when soil evaporation was high. During the dry period of 2002 (June 16th) ET was partitioned as: 3.5 mm d^{-1} (94 %) from mesquite transpiration and 0.2 mm d^{-1} (6%) from soil evaporation. On August 14th the ET was 3.8 mm d^{-1} (77%) from tree transpiration, 0.9 mm d^{-1} (18%) from understory vegetation and 0.2 mm d^{-1} from soil evaporation (5%). During these contrasting periods, the percent cover of the green understory vegetation varied from 0 to 35 % for the herbaceous dicots, and from 6 to 14 % for the bunchgrass *S. wrightii*, suggesting that an important source of the understory transpiration was from the herbaceous dicot cover (Fig. 3-8b).

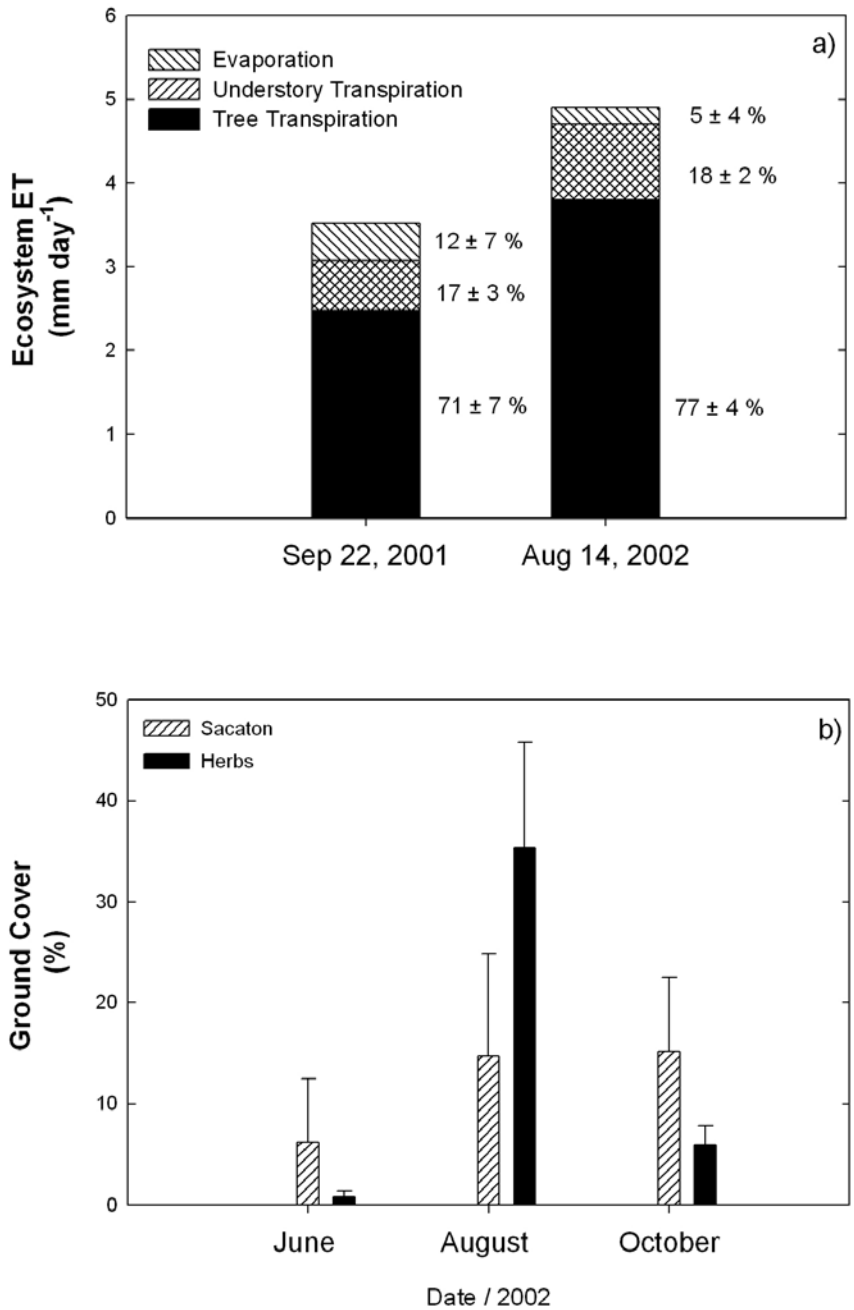

Figure 3-8. a) Total ecosystem ET partitioned into tree transpiration, understory transpiration and soil evaporation during two dates of contrasting phonologies and environmental conditions. Numbers next to bars are percentages ± 95% confidence intervals b) Absolute understory cover during the summer of 2002 for Charleston mesquite site, error bars represent the standard deviation from the mean.

Evaporation was significant only immediately after precipitation events, when volumetric water content exceeded 0.1 cm^3/cm^3 in the top 5 cm (Fig. 3-9). Following two significant rain events, on September 1st and September 14th, the combined tree and understory transpiration accounted for only 2.1 (38% of ET) and 2.6 mm d^{-1} (62% of ET) while soil evaporation represented 3.3 and 1.6 mm d^{-1} respectively (Fig. 3-9).

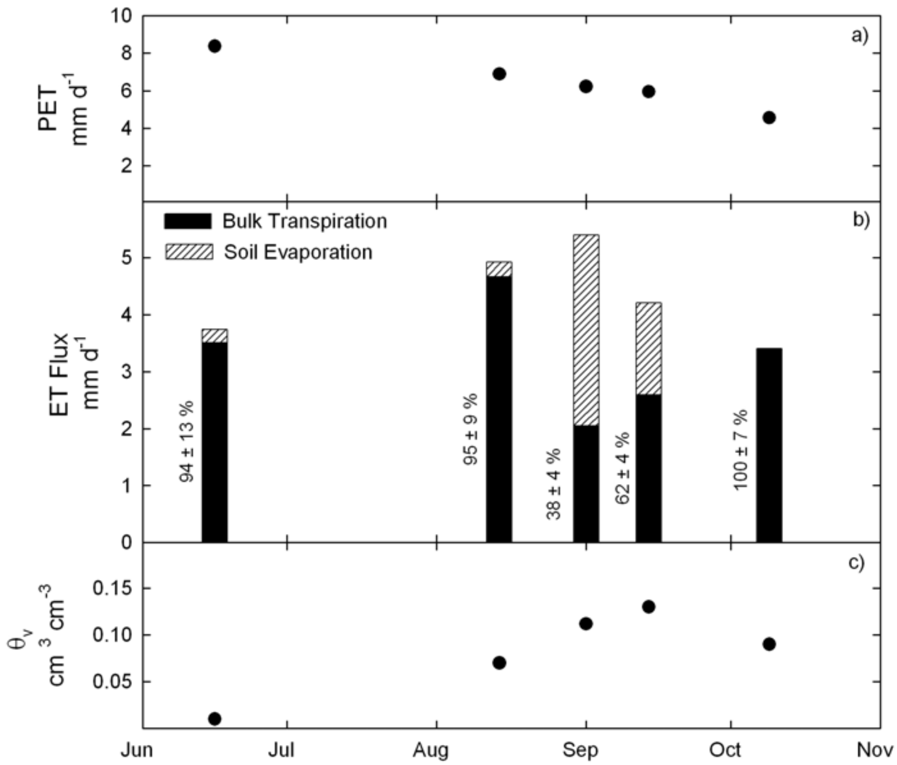

Figure 3-9. Isotopic ET partitioning in relation to seasonal precipitation a) Potential evapotranspiration, b) Isotopic flux partitioning based on the isotopic composition of plants, soil and vapor samples and measurements of ET with the eddy covariance technique, c) mean volumetric water content, from 0 to 5cm depth.

Based on the isotopic partitioning and the total ET fluxes from the eddy covariance technique we estimated the seasonal trends of ET flux components during the growing season of 2001 and 2002. Growing season was assumed to be from DOY 121 to DOY 321 for both years. (Figure 3-10). From this trend we estimated the total growing season water balance (Table 3-2).

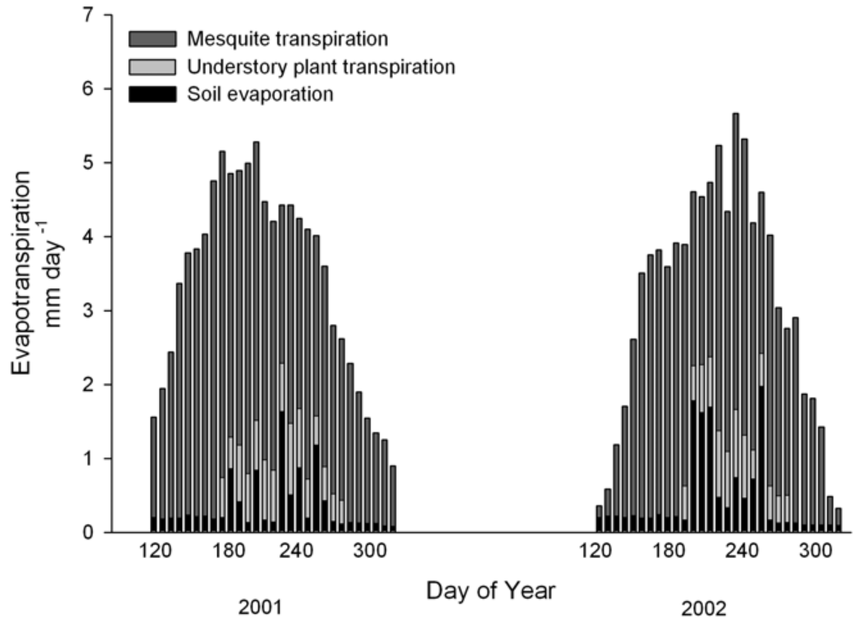

Figure 3-10. Seasonal trends of evapotranspiration flux components based on the isotopic flux partitioning and the distributed measurements of ET with the eddy covariance technique.

Table 3-2. Mesquite growing season water balance (DOY 121-321) according to isotopic partitioning. Units are in mm.

Year	Total evapotranspiration	Soil evaporation	Understory plant transpiration	Mesquite transpiration
2001	693	72	64	557
2002	636	93	54	488

3.1.3 Mesquite Water Sources

The objective of this portion of the project was to determine the seasonal and interannual patterns of water source use by mesquite. Mesquite has access to three different sources of water during the growing season: deep water in the saturated zone (groundwater); water in the deep unsaturated zone (>1m depth in soil); and water from growing season precipitation (<1m depth in soil). We predicted that mesquite, a deeply-rooted phreatophyte, would obtain the majority, if not all of its water from the deep saturated zone or capillary fringe – essentially the groundwater. The work discussed in Section 2.1 indicates that mesquite did indeed have access to the groundwater throughout the growing season, and the regular diurnal patterns of groundwater drawdown due to mesquite root uptake occurred throughout most of the season, except during limited periods during the monsoon when surface water was abundant. From this we conclude that the majority of the water used by the mesquite was groundwater. This was largely confirmed using stable isotopes. We observed for a limited number of sampling days significant uptake of water from the groundwater, but also uptake from the deep unsaturated zone and from growing season precipitation. Apparently, mesquite is very opportunistic and uses water when and where it is available. This has considerable ramifications for a groundwater budget of the riparian corridor.

Precipitation was a significant transpiration source for mesquite during the monsoon days in July, August, and September at the Charleston Mesquite, Moson, and Lewis Springs sites in 2000, 2001, and 2002 (Fig. 3-11, 3-12, and 3-13). Use of monsoon precipitation as a proportion of transpiration for mesquite was greatest at the Charleston Mesquite site in 2000 compared to that at the Moson and Lewis Springs sites (Figure 3-11). This may reflect differences in soil properties, the amount of rainfall preceding measurements, or the access to groundwater among the three sites (groundwater was deepest at the Charleston mesquite site). Mesquite relied principally on deep water (groundwater plus deep vadose zone water) with little shallow soil water uptake during the dry pre-monsoon periods. Mesquite at the Lewis Springs and Moson sites used proportionally more precipitation in 2001 than in 2002, but at the Charleston Mesquite site the proportion of precipitation used was constant at 39-40% between these years (Figure 3-12, Table 3-4).

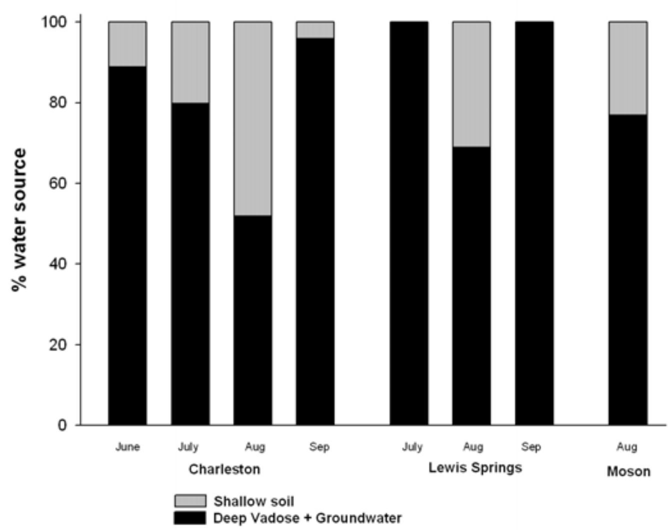

Figure 3-11. Water source partitioning for Charleston, Lewis Springs and Moson for 2000. δ^2H was used to partition between shallow and deep soil water sources.

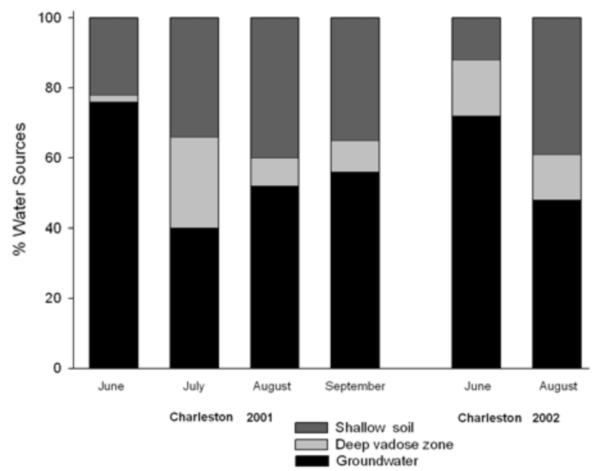

Figure 3-12. Mesquite transpiration sources at Charleston for 2001 and 2002 growing seasons. Data were obtained by relating the mesquite δ^2H and δ^{18}O isotope values to that of the three potential sources.

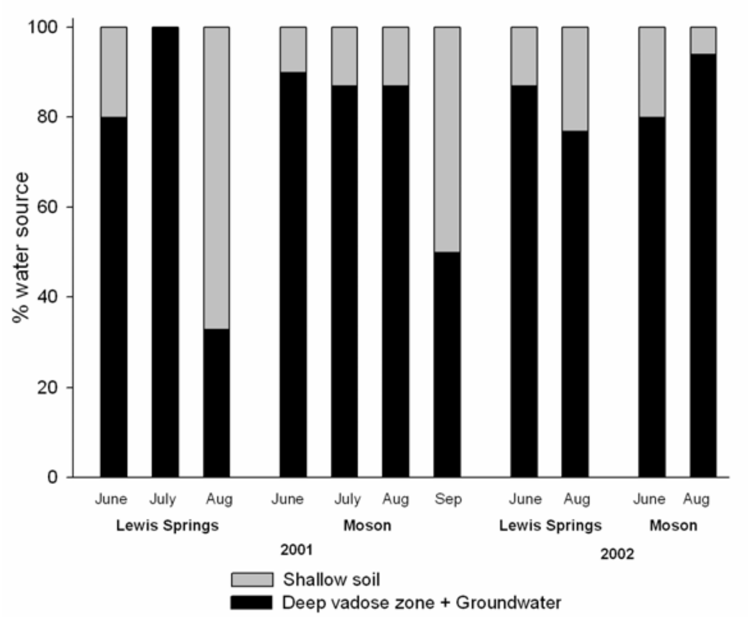

Figure 3-13. Water source partitioning for Lewis Springs and Moson in 2001 and 2002. One isotope was used to calculate water source proportions by differentiating between shallow sources and deep soil sources (Deep vadose zone plus groundwater). Because the isotope values of the two deep sources were similar at these sites, we were unable to partition these sources.

Table 3-3. Water use is partitioned by proportions (f) if total water use into shallow soil moisture (<1 m) and deep water, which includes deep vadose zone soil moisture and groundwater. SE is the standard error.

2000		June		July		August		September	
Site	**Sources**	f	SE	f	SE	f	SE	f	SE
Charleston	Shallow (<1m)	0.11	0.08	0.20	0.05	0.52	0.035	0.04	0.064
	Deep vadose + groundwater	0.89	0.08	0.80	0.05	0.48	0.035	0.96	0.064
Lewis Springs	Shallow (<1m)	-	-	0	0.32	0.31	0.025	0	0.030
	Deep vadose + groundwater	-	-	1	0.32	0.69	0.025	1	0.030
Moson	Shallow (<1m)	-	-	-	-	0.23	0.025	-	-
	Deep vadose + groundwater	-	-	-	-	0.77	0.025	-	-

Table 3-4. Water use for Lewis Springs and Moson in 2001 is partitioned by proportion of total water use into shallow soil moisture (<1 m) and deep water, which includes deep vadose zone soil moisture and groundwater. Charleston water sources are partitioned into shallow (< 1m), deep vadose zone (1-8.5m), and groundwater. SE is the standard error.

2001		June		July		August		September	
		f	SE	f	SE	f	SE	f	SE
Charleston	Shallow (< 1 m)	0.23	0.072	0.34	0.1	0.4	0.1	0.072	0.35
	Groundwater	0.76	0.06	0.4	0.27	0.52	0.28	0.56	0.14
	Deep vadose	0.02	0.072	0.26	0.17	0.09	0.18	0.09	0.09
	Deep vadose + groundwater	-	-	-	-	-	-	-	-
Lewis Springs	Shallow (< 1 m)	0.19	0.358	0	0.1	0.67	0.1	-	-
	Groundwater	-	-	-	-	-	-	-	-
	Deep vadose	-	-	-	-	-	-	-	-
	Deep vadose + groundwater	0.81	0.358	1	0.1	0.33	0.1	-	-
Moson	Shallow (< 1 m)	0.10	0.14	0.13	0.04	0.13	0.04	0.5	0.23
	Groundwater	-	-	-	-	-	-	-	-
	Deep vadose	-	-	-	-	-	-	-	-
	Deep vadose + groundwater	0.90	0.14	0.87	0.04	0.87	0.04	0.5	0.23

Deep vadose zone water contributed 2-26% of the total transpiration by mesquite at the Charleston Mesquite site in 2001 (Table 3-4) and 13-16% in 2002 (Table 3-5). Groundwater was the most important source of water at this site with June values ranging between 72-76% in 2001 and 2002.

Table 3-5. Water use for Lewis Springs and Moson in 2002 is partitioned by proportion of total water use into shallow soil moisture (<1 m) and deep water, which includes deep vadose zone soil moisture and groundwater. Charleston water sources are partitioned into shallow (< 1m), deep vadose zone (1-8.5m), and groundwater. SE is the standard error.

2002		**June**		**August**	
		f	SE	f	SE
Charleston	Shallow (< 1 m)	0.12	0.065	0.39	0.09
	Groundwater	0.72	0.13	0.48	0.18
	Deep vadose	0.16	0.07	0.13	0.09
	Deep vadose + groundwater	-	-	-	-
Lewis Springs	Shallow (< 1 m)	0.13	0.119	0.23	0.08
	Groundwater	-	-	-	-
	Deep vadose	-	-	-	-
	Deep vadose + groundwater	0.87	0.119	0.77	0.08
Moson	Shallow (< 1 m)	0.20	0.05	0.06	0.05
	Groundwater	-	-	-	-
	Deep vadose	-	-	-	-
	Deep vadose + groundwater	0.80	0.05	0.94	0.05

Mesquite transpiration at the stand level was 564 and 481 mm (see section above, Table 3-2) for the entire growing seasons of 2001 and 2002 at the Charleston Mesquite site (Figure 3-14). Groundwater accounted for the majority of mesquite transpiration with 326 and 282 mm during the growing seasons of 2001 and 2002, respectively (Table 3-6). Precipitation accounted for the second largest source with 158 and 143 mm in 2001 and 2002. Deep vadose zone water accounted for a minor yet important source of mesquite transpiration (73 and 63 mm in 2001 and 2001, respectively; Table 3-6). Therefore 55-58% of the total transpiration flux from mesquite was from groundwater in 2001 and 2002. Precipitation consisted of 29-33%, and deep vadose zone water accounted for 12-13%.

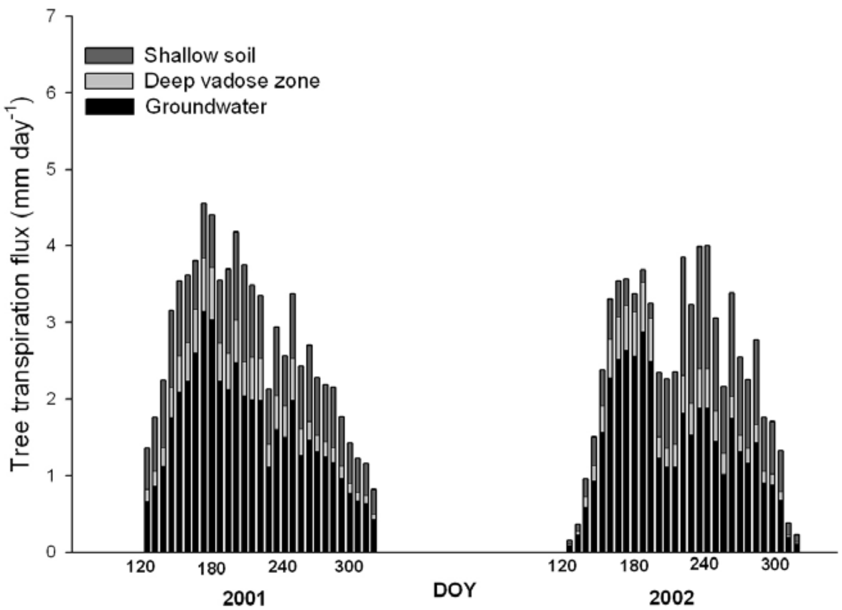

Figure 3-14. Total tree transpiration flux (mm·day^{-1}) from day 121 to 323 for 2001 and 2002 at Charleston mesquite woodland site. Transpiration is partitioned into shallow water (< 1m), deep vadose zone (> 1m), and groundwater.

Table 3-6. Total tree transpiration flux for the growing season of 2001 and 2002, at Charleston mesquite woodland site. Transpiration is partitioned into shallow water (< 1m), deep vadose zone (1 – 8.5m), and groundwater.

	Tree transpiration flux (mm)			
	Groundwater	Deep vadose zone	Shallow soil	Total
2001	326	73	158	557
2002	282	63	143	488

Uncertainty in mesquite woodland ET partitioning and groundwater use: At the Charleston Mesquite site, 136 and 147 mm of water was lost through ET from the understory in the 2001 and 2002 mesquite growing seasons, respectively (Table 3-2). Total ET in these two years was 694 and 638 mm (Table 3-1). The difference (558 and 481 mm) between total ET and that lost from the understory was assumed to be transpiration by mesquite, which was partitioned further into groundwater, deep vadose zone water, and shallow soil water sources (Table 3-6). The combined understory ET and shallow soil water use by mesquite, which is assumed to come strictly from growing season precipitation and depletion of stored surface moisture, in 2001 and 2002 was 294 and 290 mm, respectively. These values are greater than the precipitation excess (P – ΔS, Table 3-1) by 88 and 46 mm, respectively. Several factors may have led to this discrepancy. First, understory ET, especially during the dry period before the onset of the monsoon, may have come from water sources below 1 m depth. The portion of the soil profile used in the water budget calculations was 0-1 m (Table 3-1). Sacaton has roots penetrating to at least 3 m on these floodplain terraces and may be transpiring water from these deeper layers. Second, mesquite redistributes water from deep soil layers (> 1 m) to the near-surface soil during the dry periods (Hultine et al. in press), and this water may be subject to evaporation or uptake and transpiration by sacaton, leading to higher than expected understory ET. Finally, any one or all of our estimates of component fluxes and water balance may include measurement or scaling errors. These errors may have led to the inconsistency between precipitation excess and the amount of ET from the upper 1 m of soil.

3.2 Mesquite Shrubland and Sacaton Grassland

The seasonal water uses of the adjacent Lewis Springs Mesquite shrubland (LSM) and Sacaton Grassland (LSS) sites followed a very similar pattern to that seen at the CM mesquite woodland site (Fig. 3-15 and 3-16). The grassland greened up and started to transpire earlier in the year whereas the frost sensitive mesquites were more conservative. However, after mesquite leaf flush, the cumulative shrubland ET caught up to the grassland, perhaps due to an enhanced ability of the deeper rooted trees to acquire groundwater more effectively. From the start of the monsoon until the end of the growing season, the two sites had essentially the same amount of ET.

The water use pattern of the LSS site differed considerably from a similar site across the river that was monitored in 1997 – 1998 using the Bowen ratio technique (Scott et al., 2000). The earlier sacaton site was shown to have a tight coupling between precipitation and ET from which Scott et al. (2000) concluded that it used little groundwater. The cumulative water use at LSS indicates that ET was significantly in excess of precipitation—implying groundwater use by the grassland. Regular diurnal fluctuations during the growing season in a piezometer at the site confirmed this. The likely explanation for this disparity between the two grassland sites is that the earlier sacaton grassland site had a depth to groundwater of > 3.5 m, whereas at LSS it was often less than 3 m. Thus, sacaton appears to not acquire groundwater from sites where the groundwater depths are greater than ~ 3 m. This conclusion is supported by Scott et al. (2000) who mentioned that sacaton closer to the river bank (and that are closer to the water table) appeared greener in the dry season and Tiller et al (in preparation) who used stable isotopes to identify that sacaton at sites with depths to groundwater greater than around 3 m did not appear to use it.

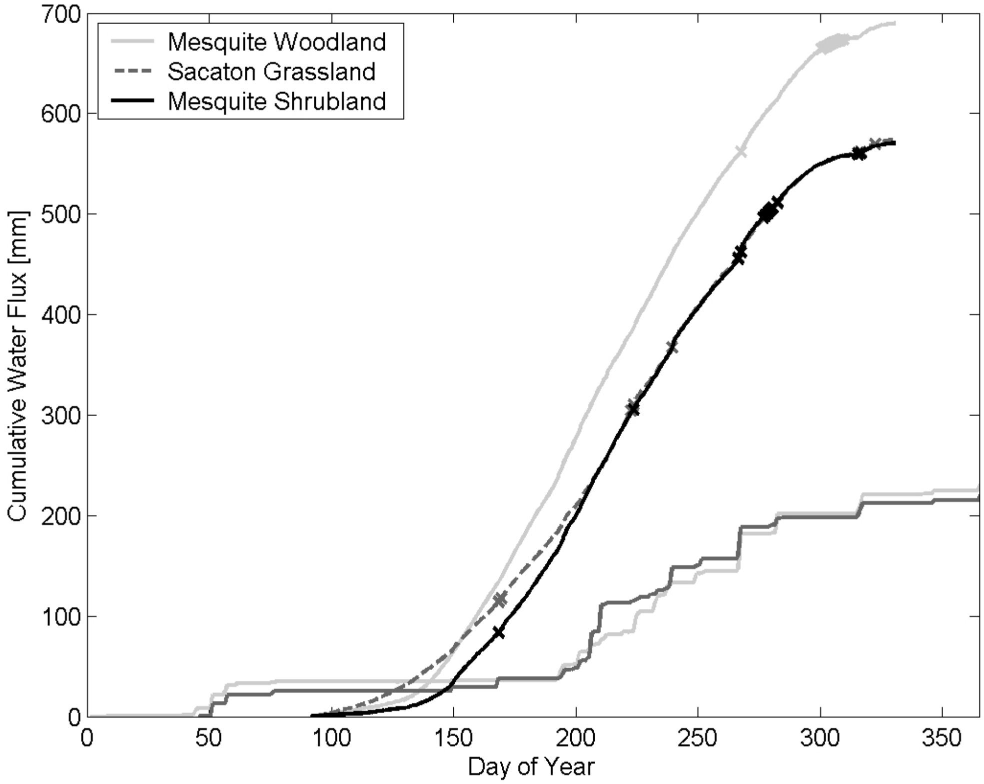

Figure 3-15. Cumulative fluxes of precipitation (bottom two lines) and evapotranspiration at all eddy covariance sites for 2003. Precipitation at the shrubland and grassland sites was essentially the same. Interpolated values are indicated with an "x". Note: only evapotranspiration data from April 1st to November 28th are shown to effectively bracket the active growing season.

The water use of the LSM site also differed from a mesquite shrubland site across the river monitored in 1997 – 1998 (Scott et al., 2000). Both sites have similar stand characteristics, but the depth to groundwater is about 3 m less at LSM. While the 1997 site did have an annual ET in excess of precipitation, the source of precipitation excess was uncertain. Scott et al. (2000) speculated that it might have been derived from deeper vadose moisture, as the fluctuations in a site piezometer did not indicate phreatophytic fluctuations. We speculate that more of the trees at LSM are able to access the groundwater perhaps due to the age distribution of the trees and the fact that the groundwater is closer to the surface.

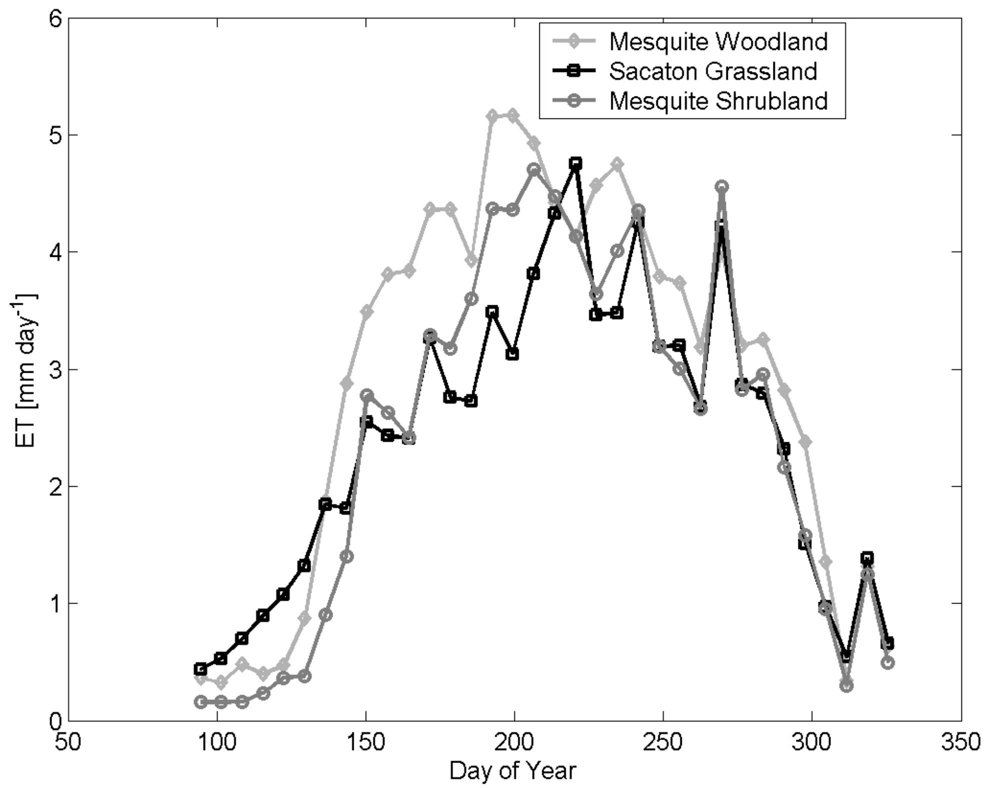

Figure 3-16. Weekly evapotranspiration for all eddy covariance sites in 2003.

Employing the growing season water balance given in Eq. 3.1, we determined the groundwater use of the LSM and LSS sites on a per unit canopy area basis and compared them to the CM site, the mature mesquite woodland site (Q_{veg}, Table 3-7). While the sacaton (LSS) site evaporation excess was the same as the adjacent mesquite shrubland (LSM), its groundwater use per unit canopy area was less due to its denser canopy area. Nevertheless, the sacaton groundwater use was significant at this site and represents a revision in our understanding of SPRNCA consumptive use. Also, it is encouraging that the LSM Q_{veg} was quite close (within 8 %) to CM's as it indicates that mesquite seem to function similarly from site-to-site. This result proved helpful for scaling up these measurements to the entire SPRNCA since the vegetation map gave us little ability to distinguish how coupled the mesquites were at any particular riparian site to the groundwater.

Table 3-7. 2003 Growing Season Water Balance (May 1 – Nov 27). Units are in millimeters. See above for term definitions

	LSS	LSM	CM
ET	554	565	676
P - ΔS	180	185	166
Q_t	374	380	510
Q_{veg}	534	633	689

3.3 Cottonwood Water Use

During the peak dry period prior to the monsoon season (July 4-9), mean daily maximum vapor pressure deficit, D, was 6 kPa at the intermittent and perennial stream sites (Fig. 3-17). D and tree water use, E, followed the same trend throughout the day. The cottonwood stand at the intermittent stream site exhibited midday depression in stomatal conductance in response to high D (Fig. 3-17). Stomatal midday depression observed at the intermittent stream site implies tight stomatal regulation of E as leaf water potential declines through the morning (O'Grady et al. 1999, Horton et al. 2001). The height of the monsoon season (August 8-13) provided a total precipitation amount of 19 mm and 4 mm at the intermittent and perennial stream sites, respectively. During this 5-d period, mean max D was almost similar to the pre-monsoon season in July with mean max D of 5 kPa (Fig. 3-18). E increased with no apparent stomatal closure at midday after significant monsoon rains and runoff events that recharged the soil moisture and groundwater at both sites. There was no dependence of E on D ($r^2 = 0.53$, p<000.1, Fig. 3-19a) at the intermittent stream site that implies reduction of hydraulic conductance along the root-shoot pathway. Soil water limitation at the intermittent stream site may have caused the decline in hydraulic conductivity during the growing season and reduced their stomatal sensitivity to D. Significant positive linear relationship of E and D at the perennial stream site indicates low resistance to water uptake (Figure 3-19a, Oren and others 1996). E appeared to be controlled by water transport capacity and amount of foliage in cottonwood trees at the perennial stream site (Cinnirella et al. 2002).

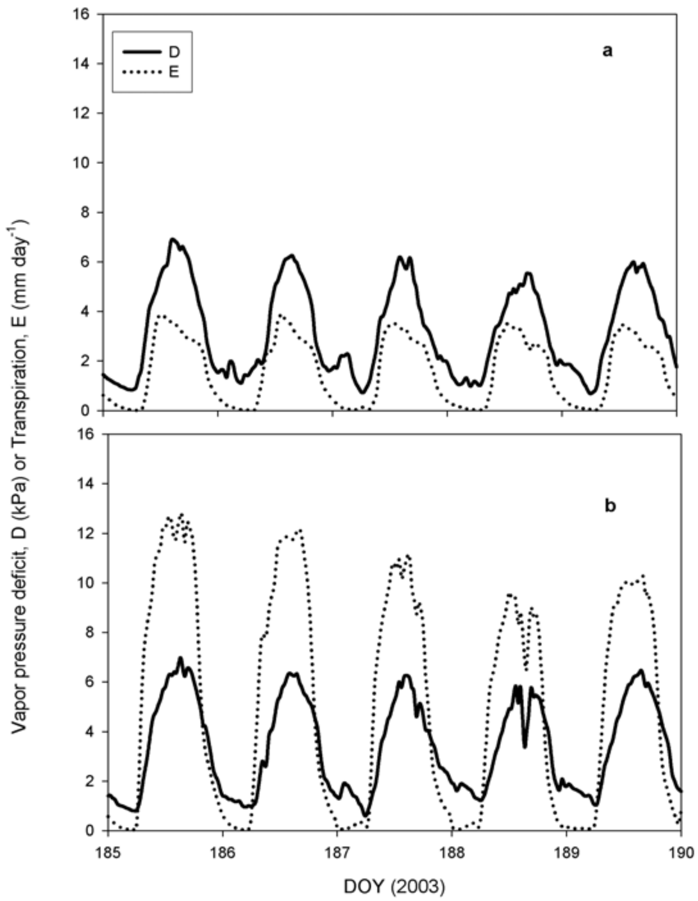

Figure 3-17. Vapor pressure deficit, D (kPa) and measured transpiration, E (mm d^{-1}) at the [a] intermittent and [b] perennial stream sites from July 4-9, 2003 (DOY 185-190). This 5-d period is part of the pre-monsoon season with mean max D of 6 kPa.

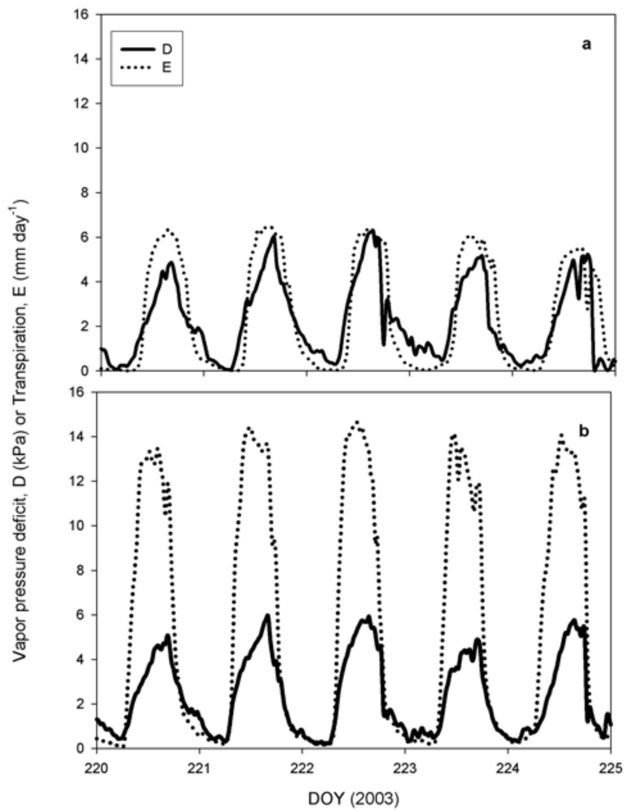

Figure 3-18. Vapor pressure deficit, D (kPa) and measured transpiration, E (mm d^{-1}) at the [a] intermittent and [b] perennial stream sites from August 8-13, 2003 (DOY 220-225). This 5-d period is part of the monsoon season with mean max D of 5 kPa.

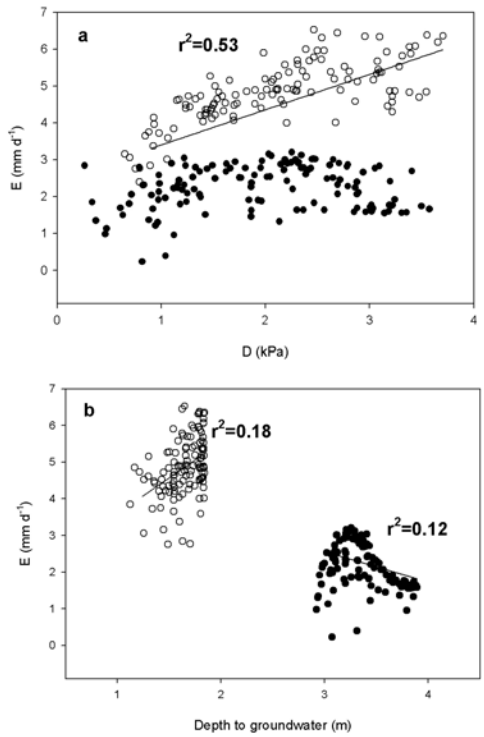

Figure 3-19. Relationship of measured transpiration, E (mm d^{-1}) and [a] vapor pressure deficit, D (kPa) and [b] depth to groundwater, GW (m) at the intermittent (closed circle) and perennial stream sites (open circle). Regression model is significant at P= 0.05.

Daily $\overline{J}_s$ (data not shown) and total daily E of the cottonwood stand at the perennial stream site were higher than the intermittent stream site throughout the growing season (Fig. 3-20). A marked decline in E at the intermittent stream site was observed during the peak of the drought or pre-monsoon season. Leaves of cottonwood trees fully leafed out at DOY 91 and completely senesced at DOY 309. Total annual stand E at the intermittent stream site was 484 mm and 966 mm at the perennial stream site. A previous study conducted at the same perennial site as this study revealed that cottonwood trees in the primary channel had higher E than trees in the secondary channel (Schaeffer and Williams 2000). On a daily basis, cottonwood trees at the perennial stream site transpired at higher rates compared to trees at the intermittent stream site indicating low resistance to the transpiration flux at the perennial stream site. Due to abundant supply of water, this suggests that atmospheric demand is the driving force for E at the perennial stream site (Oren et al. 1996). Hence, E at the perennial stream site reached close to predicted potential evaporation levels at the onset of monsoon season with high D and readily accessible groundwater table (Fig. 3-21). At the intermittent site, however, E did not increase with atmospheric demand because of increased resistance to water uptake (soil-root interface) or to transpiration (stem resistance, stomatal resistance, or reduced LAI) during drought (Oren et al. 1996, Leffler and Evans 2001).

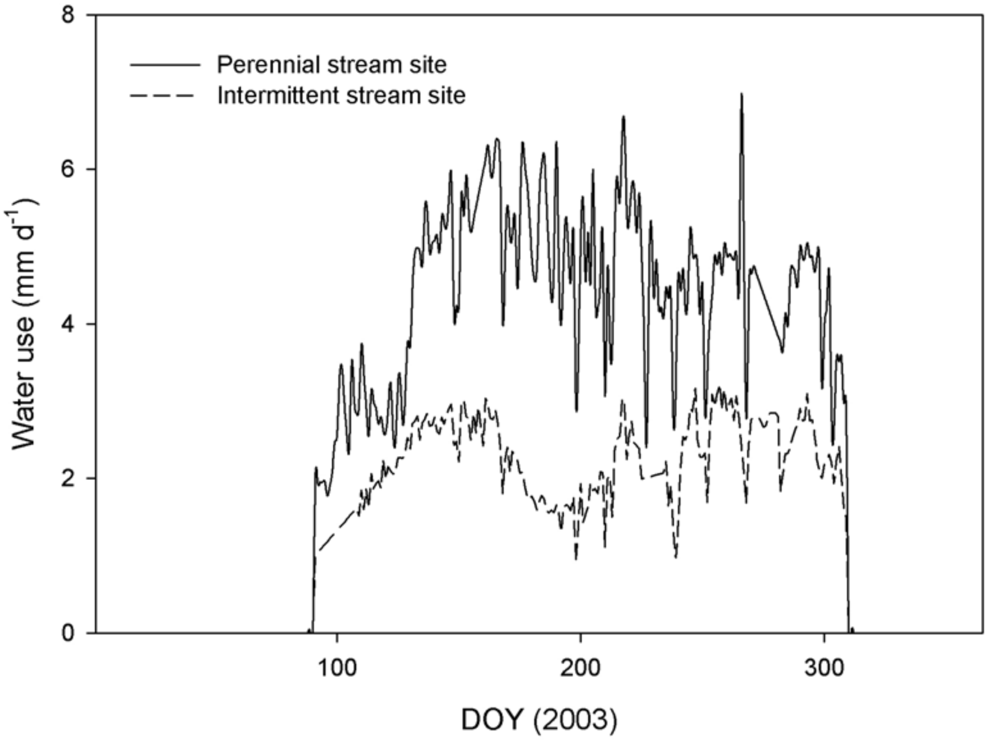

Figure 3-20. Seasonal cottonwood transpiration (E, mm d^{-1}) at the intermittent (broken line) and perennial stream sites (solid line). Transpiration at the beginning of the season was interpolated from a value of zero at the time of observed leaf flush to the measured value at the beginning of the measurement period.

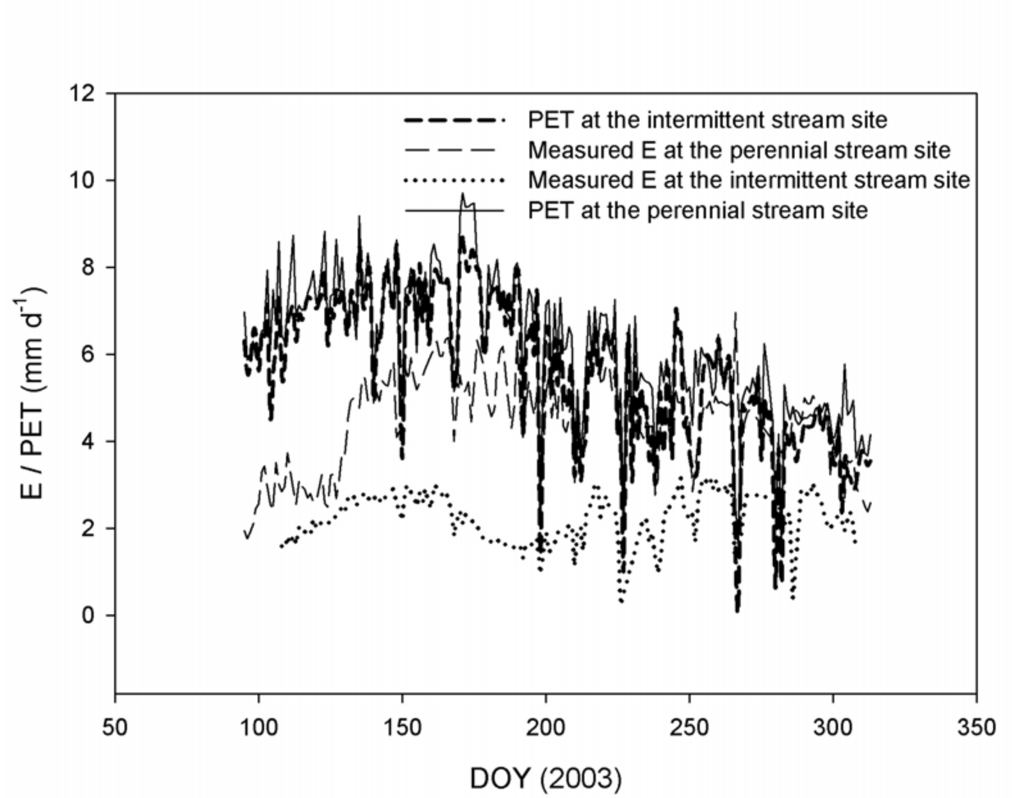

Figure 3-21. Daily reference crop evaporation, PET (mm d^{-1}) and measured transpiration, E (mm d^{-1}) of cottonwood trees at the intermittent and perennial stream sites.

During the early part of the growing season, there was a localized infestation of leaf-eating caterpillars that occurred at the perennial stream site. A decline in E started at the onset of the herbivory at DOY 113 and continued until DOY 120 when the cottonwood trees were nearly entirely defoliated (Fig. 3-20). A reduced E was observed throughout the duration of infestation. Cottonwood trees fully recovered from herbivory at DOY 130 when new leaves flushed out and E started to increase. The reduced flow observed during herbivory may be due to water used in bud swell for the production of new photosynthetic machinery. Evidence of sap flow before bud break in some species in southern deciduous forests indicated the loss of water to the atmosphere occurred through the bark, young branches and expanding buds (Oren and Pataki 2001).

Depth to groundwater, GW, at the intermittent stream site was deeper than the perennial stream site (Fig. 3-22). GW at the intermittent stream site decreased from 3.1 m during the early part of the spring season to 3.9 during the peak of the drought period (Fig. 3-22a). At the perennial stream site, GW did not vary much throughout the season except for a few peak events as a result of water table rise during the monsoon season (Fig. 3-22b). During the drought period, GW had a gradual but steady decline. The depth at the beginning of the spring season was 1.5 m and decreased to 1.1 m during the monsoon season. At the peak of the drought period, GW went down to 1.8 m.

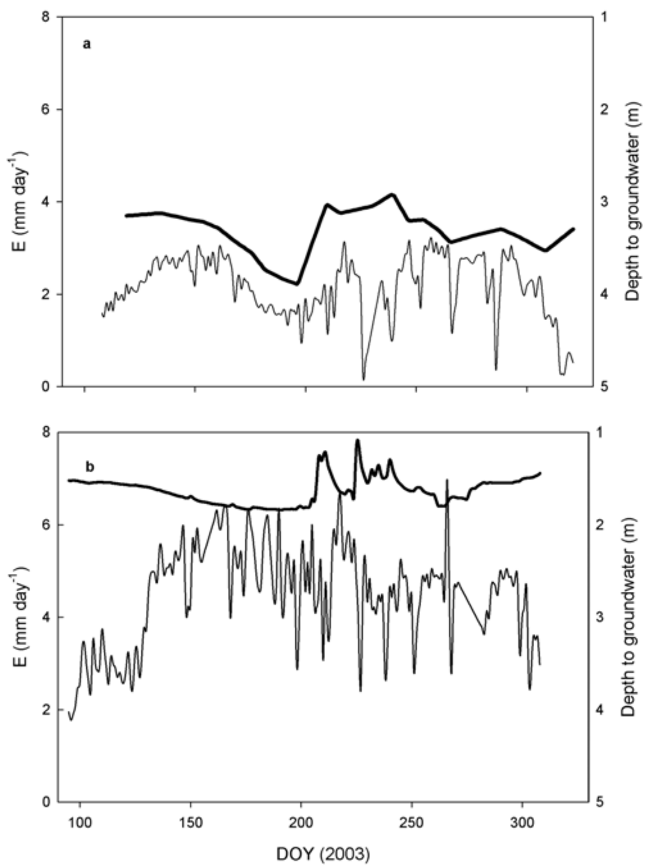

Figure 3-22. Seasonal cottonwood transpiration, E (mm d^{-1}) (thin line) and depth to groundwater, GW (m) (thick lines) at the [a] intermittent and [b] perennial stream sites.

Seasonal fluctuation in water use of cottonwood trees at the intermittent stream site was closely related to the fluctuations of the groundwater table (Fig. 3-19). Hence, there was a dependency of E to GW fluctuations at the intermittent stream site but not at the perennial stream site where GW was shallow enough to sustain high E during the summer (Fig. 3-19). Cottonwood trees at the intermittent site were dependent on shallow groundwater sources and short term perturbations of the water tables due to drought depressed E and increased water stress on these trees (Tyree et al 1994, Cooper et al. 2003, Rood et al. 2003). Transpiration of cottonwood trees at the perennial stream site responded less to changes in soil moisture because of their direct access to groundwater table (Oren and Pataki 2001). At the intermittent stream site, however, decline in groundwater table caused large reductions in E that may be associated with the loss of hydraulic conductivity that also facilitated a reduction in stomatal conductance (Cooper et al. 2003). At the onset of the monsoon rain, E at the intermittent stream site responded more to soil moisture and/or groundwater recharge by precipitation and runoff. The increase in E after the rain event was attributed to the relaxation of hydraulic resistance in the soil and soil-root interface and reversal of stem and root embolism (Oren et al. 1996, Oren and Pataki 2001).

According to previous studies, LAI of cottonwood trees at the intermittent stream site was consistently lower than the perennial stream site and was relatively constant throughout the growing season (Schaeffer and Williams unpublished data; Schaeffer et al. 2000). In October 2003, LAI at the intermittent and perennial stream sites was 1.75 and 2.75, respectively. Leaf area to sap wood area ratio was significantly higher at the perennial stream site than at the intermittent stream site (Table 2-3).

Significant negative relationship of E with GW was observed at the intermittent stream site ($r^2 = 0.12$, $p< 0.1$) and at the perennial stream site ($r^2 = 0.18$, $p<0.1$, Figure 3-19b). At the intermittent stream site, E/PET is negatively related to D ($r^2 = 0.34$, $p<0.1$, Figure 3-23a) and GW ($r^2 = 0.25$, $p<000.1$, Figure 3-17b). At the perennial stream site, E/PET was also negatively related to D ($r^2 = 0.20$, $p<0.1$) and GW ($r^2 = 0.16$, $p<0.1$, Figure 3-23b). As GW became deeper, E/PET ratio declined. E/PET ratio that has a value of more than one implies non-stress conditions, E/PET considerably less than one (< ~0.8) implies drought stress conditions. Critical depth to groundwater at the intermittent stream site was estimated to be at approximately 3.4 m beyond which E/PET dropped off considerably.

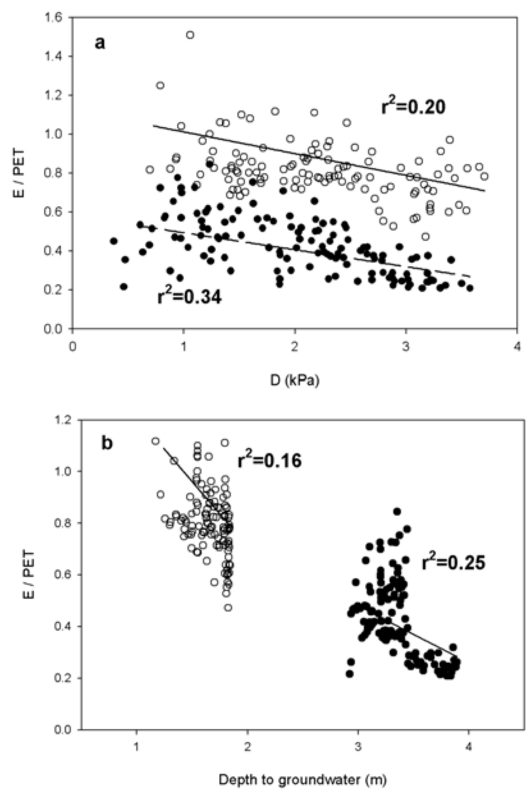

Figure 3-23. Relationship of the ratio of measured transpiration and reference crop evaporation (E/PET) and [a] vapor pressure deficit, D (kPa) and [b] depth to groundwater, GW (m) at the intermittent (closed circle) and perennial stream sites (open circle). Regression model is significant at P= 0.05.

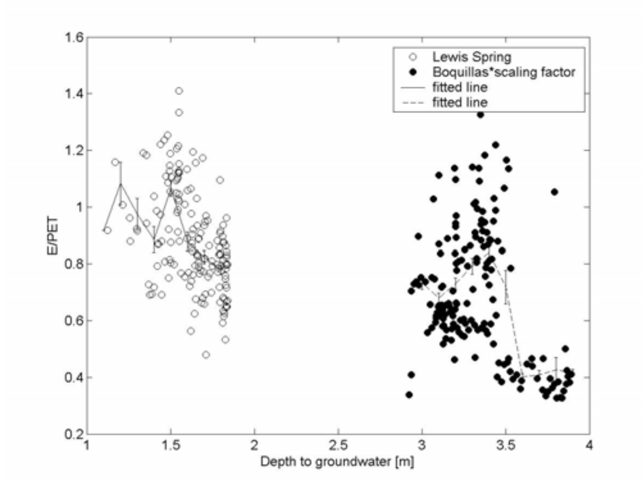

Figure 3-24. Relationship of the ratio of measured transpiration and reference crop evaporation, E/PET and depth to groundwater, GW (m) at the intermittent (Boquillas, closed circle) and perennial stream sites (Lewis Spring, open circle). Scaling factor of 1.57 was used to scale E at the intermittent stream site based on LAI.

3.4 Seep Willow Transpiration and Open Water Evaporation

This field study was conducted in 2002 and 2003 in order to make transpiration measurements from a dominant understory species and from an open water surface below the cottonwood gallery. These are the first ET measurements made from these two cover types along the San Pedro River. Previous estimates of riparian corridor groundwater discharge have estimated the open water evaporation analytically using empirical formulae and commonly available meteorological data. Groundwater use by obligate phreatophytic understory plants has been completely ignored due to the difficulties of making such measurements. Further, the total area covered by such plants is thought to be insignificant compared with the cover of other vegetation elements in the riparian corridor.

A list of major understory species was provided by ASU, and visual surveys of active, green understory plants were made in June 2002 prior to the monsoon. Green understory plants were an indicator that the species did rely upon groundwater as a water source. From these surveys, seep willow and sacaton turned out to be the dominant understory vegetation types that are probable groundwater users.

3.4.1 Understory seep willow water use

Due to instrumentation problems and the difficulty of working within an active floodplain, much of the 2002 measurements were not reliable. In 2003, seep willow sap flow was measured at both open and closed canopy sites from May 30 to November 13 (DOY 150-317) encompassing pre-monsoon, monsoon and post-monsoon periods. We compared transpiration from both sites with cottonwood water use and reference ET, ET_o, (Fig. 3-25) and found that the seep willow had water use rates comparable to that of the cottonwood forest. ET_o was calculated using meteorological data from the Lewis Springs Met Site that was located in a more open environment. We expect that ET_o in the understory floodplain environment would be somewhat less than for exposed forest canopies. Prior to the monsoon, atmospheric demand (represented by ET_o) did not appear to be limiting as the seep willow transpiration was nearly constant and was not responsive to daily fluctuations in demand. Also, both the more open and more closed sites had similar transpiration rates. During this time, stand transpiration for both sites was limited to about 5 mm/day. After the monsoon began around DOY 200, atmospheric demand was lower and the seep willow transpiration was more responsive to its fluctuation, indicating more demand limitations during this time.

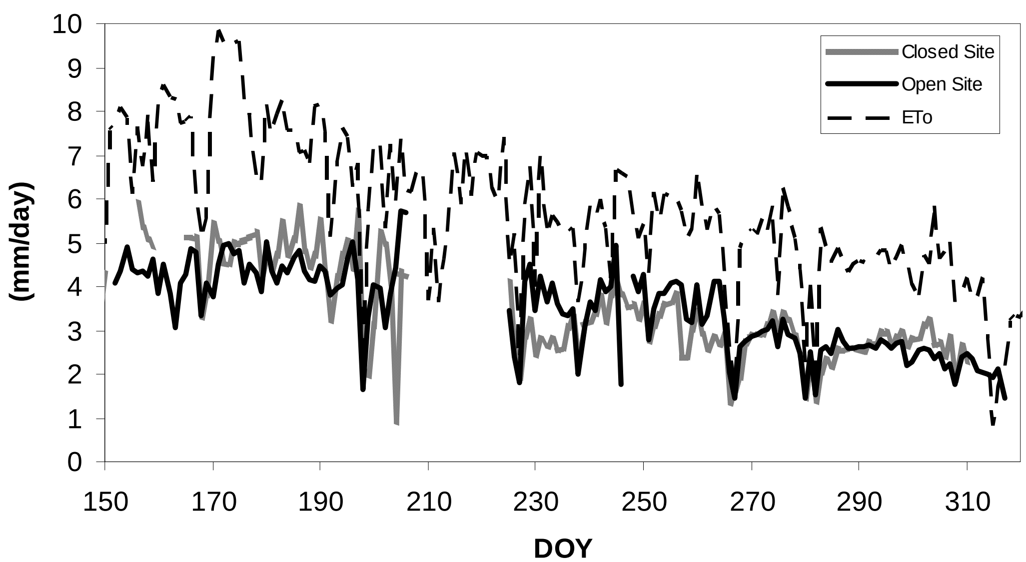

Figure 3-25. Comparison of seep willow transpiration with reference ET at Lewis Springs East Site.

At the time of this report, the approach to estimate entire growing season consumptive use by seep willow had not been developed, but the measurements indicate that seep willow consumptive use at the stand level might be as large as any of the other vegetation types studied. Also, accurate estimates of understory vegetation amounts in the floodplain were unfortunately not available to scale up stand level estimates to the reach level. Nevertheless, we used vegetation transect surveys and reach information provided by ASU to compute a rough estimate of seep willow amount within the SPRNCA (Table 3-8). Based on this preliminary work, the amount of seep willow within the SPRNCA was small in comparison with the other major cover types (see Table 4-3, Section 4-2). However, if one considers the potential consumptive use of seep willow along with the additional *understory* plants like sacaton, then including them in the overall water budget would increase SPRNCA consumptive use estimates.

Table 3-8. ASU reach length, average floodplain width, seep willow percent cover, and estimated seep willow amount for the entire reach.

Reach #	Reach length (km)	Floodplain width (m)	Seep willow cover (%)	Seep willow amount (ha)
1	8.1	203	2.05	3.4
2	7.6	155.5	2.1	2.5
3	6.1	185	3.4	3.8
4	2.3	305	1.7	1.2
5	6.5	175	1.8	2.0
6	3	269	2.1	1.7
7	4.1	64	1.3	0.3
8	5.8	112.5	3.9	2.5
9	3.1	83	4.75	1.2
10	1.9	140	1.8	0.5
11	2.1	63	4.7	0.6
12	4.7	350	4.7	7.7
13	3.9	306	1.2	1.4
14	2.5	143	2.7	1.0
			TOTAL	**30.0**

3.4.2 Channel evaporation

We found good agreement between the daily variation in the mean small pan evaporation rates and ET_o (Fig. 3-26). Previously, Goodrich et al (2000) estimated open water evaporation as a fraction of the Penman open water evaporation to account for the more shaded streamside environment:

$$E_{ow} = f\ E_p \tag{3.X}$$

where E_{ow} is the open water evaporation (mm day^{-1}), f is the reduction factor (0.6 in this case), and E_p is the Penman evaporation. Our current study at Lewis Springs shows that the average ratio between the ET_o and the measured evaporation was 0.73.

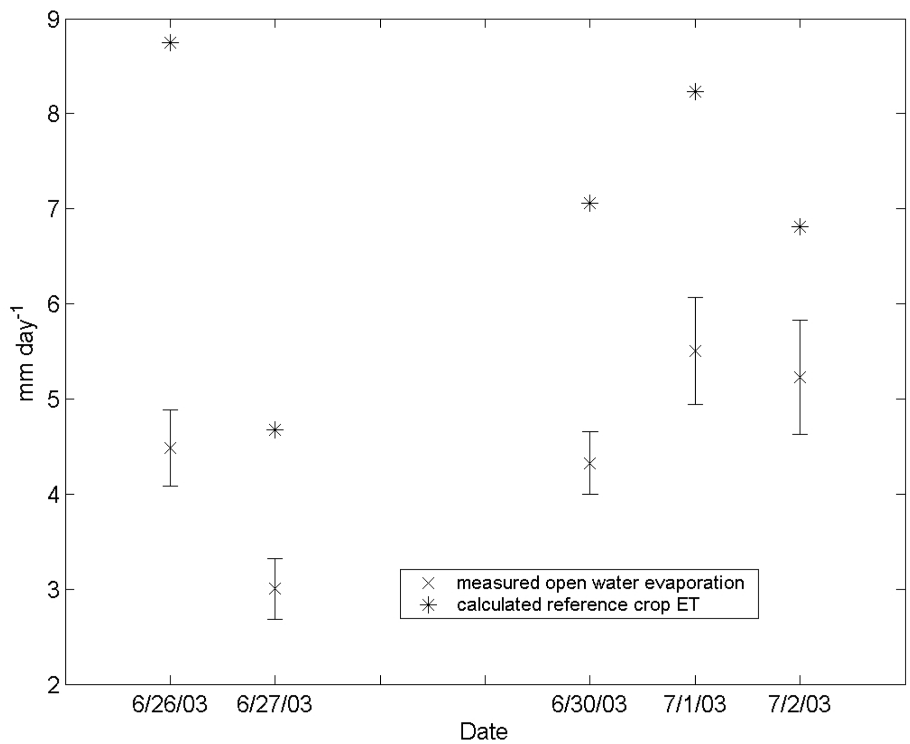

Figure 3-26. Measured +/- one standard error (X's) versus calculated open water evaporation (*) in 2003. The measurements were made using a network of 12 small pans distributed throughout the understory environment of the cottonwood gallery forest, and the calculated reference crop ET was computed using data from a nearby met station outside of the forest using AZMET standards. The average ratio between the measured and the calculated values is 0.73.

4 Riparian Corridor Groundwater Use

Section 3 provided the detailed results of our water use studies for the dominant vegetation types along the Upper San Pedro that use groundwater. This section documents how these results were scaled up to estimate total SPRNCA groundwater use. In order to do this, we needed to combine our understanding of how the major vegetation types used water to determine a representative annual groundwater use rate for that vegetation type. Once the groundwater use rate for each major vegetation type was estimated we then multiplied these rates by their respective vegetation areas determined from the vegetation map.

4.1 Vegetation Groundwater Use

We chose to estimate SPRNCA vegetation consumptive use for 2003 only since simultaneous measurements of the cottonwood forest, sacaton grassland and mesquite shrubland were only available during this year. We used 2003 measurements from the mesquite woodland in this exercise so that all of the revised estimates come from the same growing season. An alternative to choosing one year to estimate water use would be to use these measurements to build and calibrate component models of each vegetation functional group (e.g., cottonwoods along intermittent reaches) which could be used to model water use in any given year that meteorological data and amount of each cover type was available to drive the models. For purposes of this report, this alternative was not selected because: (1) not enough data were collected (with the possible exception of the mesquite woodland site) to capture interannual variability, and (2) the incorporation of modeling would only lead to more uncertainty in our results. Future data collection and analysis hopefully will lead us to a point where we can accurately understand what determines the water use rates and then capture this understanding in a model environment

The following summarizes how the vegetation groundwater use estimates made in this study (Table 4-1) were derived:

1. Mesquite. All mesquite located within the riparian corridor of the SPRNCA were assumed to have the 2003 groundwater use of mesquite at the CM site (Section 3.1). The groundwater use rate per unit mesquite canopy area was derived from the growing season water budget (Table 3-1). The 2003 water balance figure was used because: 1) all other vegetation ET measurements were only available in 2003, 2) there was no isotope method estimates for this year, and 3) the mass balance method involved the least number of assumptions. We feel this will result in a 2003 estimate that is conservatively high given the possible effects of hydraulic redistribution by the mesquite throughout the deeper vadose zone. Additionally, there are younger, smaller mesquite trees within SPRNCA that are of insufficient size to tap into the groundwater but nevertheless are part of the total mesquite area. This also results in our estimate of mesquite groundwater use being conservatively high.

2. Cottonwood/Willow (Perennial). All cottonwood/willow stands located along mostly perennial reaches where the maximum depth to groundwater was estimated not to exceed 3 m were assigned the growing season total estimated by the 2003 sap flow studies at Lewis Springs (Section 3-3). The portions of the SPRNCA that met these qualifications were delineated by ASU's Reaches 2-7. Snyder and Williams (2000) using isotopic data suggest that the cottonwoods at the perennial Lewis Springs Site, derived most of their water from groundwater sources. Thus, we assumed that the seasonal total water use of the cottonwoods along perennial reaches was derived completely from groundwater.

3. Cottonwood/Willow (Intermittent). All cottonwood/willow stands located along intermittent reaches where the maximum depth to groundwater did exceed 3 m or more were assigned the growing season total estimated by the 2003 sap flow studies at Boquillas (Section 3-3). Using the reach definitions and information provided by ASU, the trees in reaches 1, and 8 – 14 were assigned this category. We assumed that all of the trees water use prior to the start of the monsoon was derived from groundwater. After the start of the monsoon and the water table recovery on DOY 201 and until tree senescence, we assumed that 70% of the daily total transpiration

was derived from groundwater following Snyder and Williams (2000) who studied a cottonwood site with similar groundwater depths. In 2003, we made multiple leaf water samples for isotopic source water analysis and these results should help to refine the percent groundwater use of the cottonwoods at both sites. The estimated total groundwater use was 407 mm (Table 4-1) and 84% of the total season transpiration of 484 mm.

4. Sacaton (< 3 m depth to groundwater). The total canopy area of sacaton grasslands where the estimated depth to groundwater was 3 m or less was assumed to have the 2003 water use of sacaton at the LSS site (Section 3-2). Using LiDAR measurements and GIS analysis (Section 2-5), the region where the estimated depth to groundwater was less than 3 m was delineated by the area that fell within the 3 m contour height above the cross-section low point -- assuming that the water table height under the land surface perpendicular to the thalwag had the same elevation as the cross section low point. The amount of sacaton within this area was estimated by intersecting this delineated region with the vegetation map. The groundwater use rate per unit sacaton canopy area was derived from the growing season water budget (Table 3-7).

5. Salt Cedar. Because salt cedar was not measured in this study, we assume that these trees had a water use equal to that of the mesquite. Reasons for this assumption are that the trees have a similar stand structure and both are able to acquire groundwater from deeper sources than cottonwoods. Dahm et al. (2002) reported a total ET of 740 – 760 per year for Salt Cedar at medium-density stand of salt cedar along the Middle Rio Grande, NM. This was ~300 mm less than a dense stand of salt cedar and a mature cottonwood stand growing along the same reach. Our measurements of mesquite and perennial cottonwood differ by a similar amount.

6. Open Water. Open water evaporation estimates were derived from the total 2003 reference crop evaporation, ET_o, calculated using data from the met site at Lewis Springs (Appendix B). This rate was multiplied by a factor of 0.73, which represents the ratio of average small pan evaporation rate located near or within the streambank and the calculated AZMET reference crop evaporation (Section 3.4.2).

Table 4-1. 2003 consumptive use rates [mm]

Cover Type	
Mesquite	690
Cottonwood/Willow (Perennial)	970
Cottonwood/Willow (Intermittent)	410
Sacaton	530
Open Water	1210

4.2 Vegetation Areas

The change from the grid-based vegetation map, VEG97, used by Goodrich et al. (2000) to the polygon-based GIS coverage, VEG00 (US ARMY Corps of Engineers), used in this study resulted in dramatic changes in vegetation area. As an example of this shift, there was a distinct change in the total amount of area covered by each of four groundwater-using groups along the San Pedro between the Palominas and Tombstone USGS gages (Table 4-2). The range given for the VEG00 map represents the minimum and maximum amounts. Recall that many of the vegetation polygons had an assigned range instead of an exact percent cover. The amount of riparian vegetation was calculated as the product of the total polygon area and the percent cover (single value or range). The open water amount is the entire polygon area. For the areas listed in Table 4-2, all cottonwood/willow polygons had an exact area given to them, which was not the case for the sacaton and mesquite amounts.

Table 4-2. Comparison of the amount of riparian vegetation [ha] along the San Pedro between the Palominas and Tombstone gages using the maps of Goodrich et al. (2000) and this study.

	Vegetation Map	
Cover Type	Veg97	Veg00
Mesquite	1166	718 - 964
Cottonwood/Willow	526	308
Sacaton	382	362 - 512
Open Water	5	41

In this report, we accounted for the uncertainty in the vegetation amounts by computing a range of water use for each plant functional type. This range was computed by using the minimum and maximum vegetation areas and multiplying each by the appropriate water use amounts. Nonetheless, the change in amount of vegetation between maps will clearly result in a large change in the water use calculations from those previous estimated by Goodrich et al. (2000). In fact, the magnitude of this change (~ 40% for some vegetation types) is as large as any changes resulting from the refinement of plant groundwater use. While there have been some natural vegetation cover changes, mainly due to fires, from 1997 to 2000, it is unlikely that all this change is natural.

Table 4-3 presents the vegetation amounts for the San Pedro riparian corridor from the southernmost to the northernmost boundary of the SPRNCA. Table 4-4 lists the amounts for the riparian corridor from the International border to the USGS gage at Tombstone, a reach that has been used to define the consumptive use in the Sierra Vista Sub-basin alone. For this report, the amount of riparian vegetation within the private land inholdings just south of the Charleston Gage was included. The amount of groundwater using vegetation within these lands turned out to be relatively small (Table 4-5) since most of the riparian corridor fell outside of the property boundaries.

Table 4-3. Total SPRNCA vegetation area [ha] for major groundwater using communities

Cover Type	Veg00

Mesquite	1154-1456
Cottonwood/Willow (Perennial)	253
Cottonwood/Willow (Intermittent)	177
Sacaton (< 3 m to groundwater)	113-168
Open Water	73
Salt Cedar	72-108

Table 4-4. Sierra-Vista Sub-Basin riparian vegetation areas (ha)

Cover Type	Veg00
Mesquite	723-973
Cottonwood/Willow (Perennial)	253
Cottonwood/Willow (Intermittent)	118
Sacaton (< 3 m to groundwater)	113-167
Open Water	43
Salt Cedar	1-3

Table 4-5. Riparian vegetation areas (ha) within the private land inholding just south of the USGS gage at Charleston.

Cover Type	Veg00
Mesquite	2.4-3.6
Cottonwood/Willow (Perennial)	4.6
Cottonwood/Willow (Intermittent)	-
Sacaton (< 3 m to groundwater)	-
Open Water	0.1
Salt Cedar	-

4.3 Riparian Corridor Groundwater Use

Vegetation amounts (Tables 4-3 and 4-4) were multiplied by their respective consumptive use rates (Table 4-1) to determine riparian corridor consumptive use (Tables 4-6, 4-7). Mesquite consumptive use was the dominant component of the water budget with cottonwood/willow, open water, sacaton, and salt cedar, respectively, of decreasing importance. For the entire SPRNCA consumptive use, we were unable to find any previous estimates for comparison. Our 2003 estimate for the consumptive use from the International border to the Tombstone gage was 11 - 36 % higher than Goodrich et al. (2000) due to the combination of using the VEG00 map and the new water use estimates. Corell and others' (1996) estimate of 9498 x 10^3 m^3 yr^{-1} (7700 ac-ft) for riparian consumptive use within the Sierra Vista Sub-basin fit within the range of our estimates.

Table 4-6. Total San Pedro riparian consumptive use within the SPRNCA and along the main stem of the San Pedro River. Range given reflects the minimum and maximum amounts due to the uncertainty in the vegetation areas.

Cover Type	1000 m^3 yr^{-1}	acre-ft yr^{-1}
Mesquite	7963-10046	6455-8145
Cottonwood/Willow (Perennial)	2444	1981
Cottonwood/Willow (Intermittent)	720	584
Sacaton (< 3 m to groundwater)	599-890	486-722
Open Water	883	716
Salt Cedar	497-745	403-604
Total	13105-15729	10625-12752

Table 4-7. San Pedro riparian consumptive use along the main stem of the San Pedro River from the International border to the Tombstone Gage. Range given reflects the minimum and maximum amounts due to the uncertainly in the vegetation areas.

Cover Type	1000 m^3 yr^{-1}	acre-ft yr^{-1}
Mesquite	4989-6714	4044-5443
Cottonwood/Willow (Perennial)	2444	1981
Cottonwood/Willow (Intermittent)	480	389
Sacaton (< 3 m to groundwater)	599-885	486-718
Open Water	420	421
Salt Cedar	7-21	6-17
Total	9039-11064	7328-8969
Corell et al. (1996)	9498	7700[a]
Goodrich et al. (2000)	8130	6590[b]

[a]Using baseflow information from the Palominas, Charleston, and Tombstone Gages.
[b]From the international border to the Tombstone Gage

It is important to realize that these water use calculations are based on 2003 measurements. With just three years of mesquite ET data, we have found that the mesquite water use from year to year was quite variable (e.g., as much as 22% less, relative to 2003). The main sources of the seasonal variability were the climatic drivers that determine the length of the growing season, the amount of rainfall, and the atmospheric evaporation demand. It is reasonable to expect that the other vegetation communities' consumptive use would also have similar variability. Based on this very limited amount of data, estimates for 2003 were likely higher than what might have been expected for 2001 and 2002 due to the longer growing season (see Appendix 2, Table B-2) and the lower amount of winter and monsoon precipitation.

5 Future work

Much has been done to improve our understanding of consumptive use along the Upper San Pedro River. Nevertheless, future research will refine our estimates and provide the knowledge needed to predict patterns of consumptive use under future land cover and climate conditions. The following research and monitoring is planned to reduce the uncertainty of riparian consumptive water use.

1. Cottonwoods: Numerous samples of leaf water isotopes were collected over the 2003 season at the intermittent and perennial reach. These samples are being analyzed to determine more accurately the percent of groundwater that was transpired at both sites.

2. Mesquite: We will continue to monitor mesquite woodland and shrubland water use to improve our understanding of interannual variability of ET. By monitoring root sap flow and deep vadose zone moisture content, we also will work to determine the role that hydraulic redistribution and deep vadose zone moisture plays in mesquite functioning

3. Sacaton: On-going monitoring will continue to improve our understanding of interannual variability of ET for this ecosystem type.

4. Understory: Work continues on quantifying the seasonal amount of groundwater used by understory vegetation (e.g., sacaton, seep willow). This is being done by scaling up limited sap flow observations to seasonal totals and by developing new methods to determine understory vegetation amounts.

5. Modeling: Data will be used to develop models to predict water use by species, depth to groundwater and observed weather.

6. Remote sensing: Remote sensing offers the promise of improved up-scaling of our site-based measurements. We are working to determine if a good correlation can be found between *in-situ* measurements of ET and remotely-sensed measurements of a vegetation or greenness index. These relationships would then be used as an alternative approach to determining riparian vegetation water use.

7. Vegetation mapping: The ARMY COE is scheduled to develop new SPRNCA vegetation maps in 2004 and 2008. We will work with COE to develop a map which will allow us to determine vegetation amounts more accurately.

6 Acknowledgements

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Appendix A: GIS-based Riparian ET Tool

Multiple meetings with the USPP and BLM have been carried out to develop a GIS-based tool for determining SPRNCA water use. The tool has a user-friendly interface that allows for easy manipulation of a vegetation map and projection of the seasonal demand of groundwater-using vegetation. The tool calculates the total amounts of different types of phreatophytic vegetation from a vegetation map of the riparian corridor of the Upper San Pedro River, and then multiplies these amounts by the appropriate seasonal groundwater demand per unit area of vegetation to calculate the total groundwater use.

ArcView GIS (ESRI, Redlands, CA) supplies the structure on which the tool is built, and easy-to-use menus with complete instructions are included. The tool is designed to work with the riparian corridor extracted from the Army Corps of Engineers Vegetation Map of the SPRNCA, dated 2001. Groundwater use for the entire length of the SPRNCA or any combination of contiguous reach maps (provided with the tool) may be calculated. The user may change any type of vegetation anywhere on the map. Out of the many different types of vegetation and land cover in the San Pedro riparian corridor, we have identified the following cover types as likely groundwater using candidates: mesquite, cottonwood/willow, sacaton grass, and open water categories.

To modify the vegetation map, the user either supplies a polygon map of the area to be revised (i.e. a prescribed burn), or is prompted to draw a polygon of the area to be revised directly on the vegetation map.

Upon starting the tool, the user is first asked if he/she wants to analyze the entire SPRNCA or just a portion.   To analyze just a portion of the SPRNCA, the user selects the desired reaches and the tool combines them into a new map. Then the user is presented with a screen showing four choices of vegetation manipulation. If the user wants to analyze the entire SPRNCA, this screen is shown immediately. The choices for vegetation manipulation are:

1) vegetation within a user-defined polygon is changed to a new type of vegetation (e.g., sacaton) and ET is calculated;
2) one vegetation type within a user-defined polygon is changed to a new type of vegetation (e.g., change salt cedar to cottonwood) and ET is calculated;
3) all vegetation within a user-supplied polygon map is changed to a new type of vegetation (e.g., change a prescribed burn area to bare soil) and ET is calculated;
4) calculate ET for the selected map without any change in vegetation.

If option number 1 is selected, a new screen appears asking the user to select the grid to modify, the new vegetation type, and the name of the new map to create. If the user has chosen option number 2, the new screen also requests the type of vegetation to change from. For either option the user must also specify the percent cover of the new type of vegetation. For option 3, the user is asked to select the polygon map to use for analysis, the new vegetation type, and the name of the new map to create. This option may be used to analyze a prescribed burn or other types of vegetation manipulation where a polygon map of the area to be modified is available.

If either of the first two options is selected, the user is instructed to draw a polygon using the mouse of the area of interest. After the polygon is drawn, the tool performs the specified vegetation revisions, creates the new map, and calculates the new groundwater use values for the entire riparian corridor under a historically observed climate. When a user supplied polygon map is selected, the "draw polygon" step is skipped, the tool immediately calculates the change in groundwater use based on the polygon map, and presents the results. Using this option, the progression of vegetation re-growth after a prescribed burn or wildfire can be analyzed for water use.

The results are presented as a plot against the values calculated from the original, unaltered map. In all cases, the original vegetation map is not changed; a new map is created. The newly created maps may then be used for subsequent analyses.

Appendix B: Comparison of Meteorological Forcing At Three Riparian Sites

With the helpful cooperation of Fort Huachuca, three met towers to monitor basic meteorological variables (air and soil temperature, relative humidity, wind speed, wind direction, air pressure, solar radiation and precipitation) have been in operation since the fall of 2000 within the SPRNCA. These towers are located near the Palominas-USGS (PM, elev. 1290), Lewis Springs (LS, elev. 1240), and Charleston Mesquite (CM, elev. 1200) Transects to understand how meteorological forcing, one of the primary drivers for the vegetation water use, varied within the SPRNCA. See Fig. 1-1 for station locations. A previous model to determine SPRNCA water use employed by Goodrich et al. (2000) assumed that the forcing measured at the intensively monitored SALSA site near Lewis Springs could be used for the entire SPRNCA water use calculations. We wanted to determine if this was an accurate assumption.

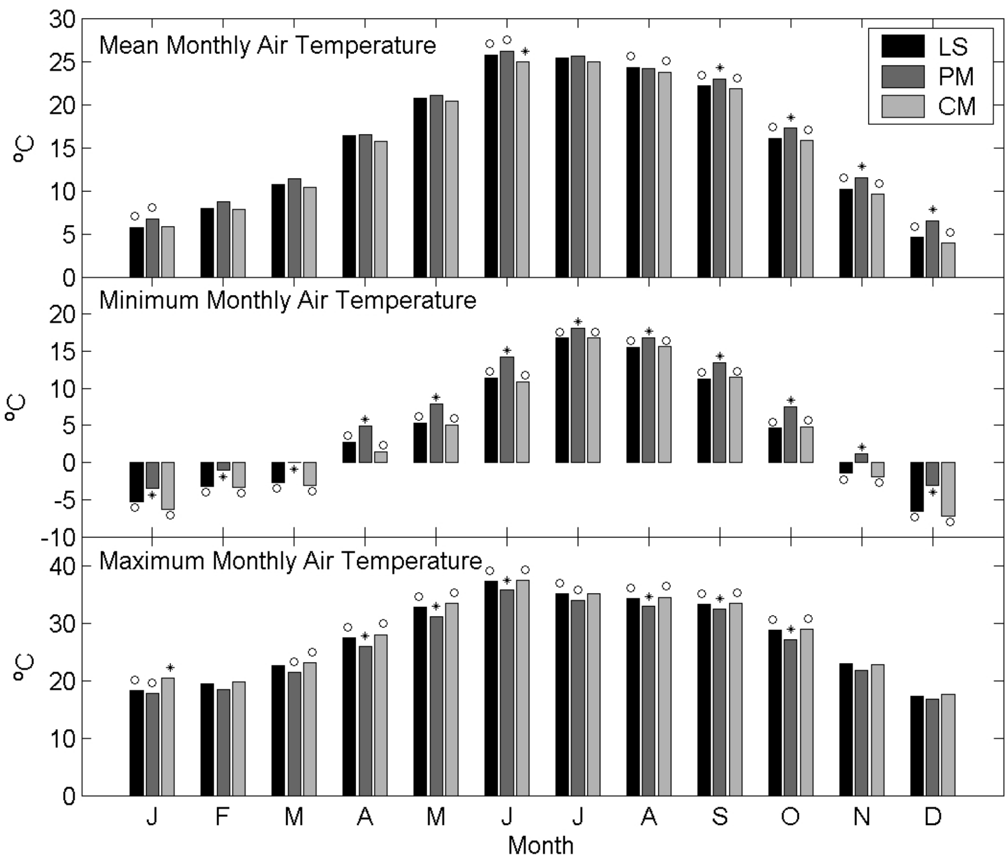

Figure B-1. The 2001 – 2003 average monthly mean, minimum, and maximum daily air temperatures for the Lewis Springs (LS), Palominas (PM), and Charleston Mesquite (CM) met sites. The daily mean, minimum, and maximum temperatures were computed for each day at each site, and then these results were averaged on a monthly basis. Averages that were significantly different (p = 0. 05) from the other two sites are indicated by an asterisk, and those that were significantly different (p = 0. 05) from one of the other sites are indicated by a circle.

Air temperatures were measured from 2001 through 2003 at 3 m above ground at CM and 2 m at PM and LS. Mean daily temperatures were quite similar across all sites, though CM was generally cooler than the higher elevation sites (Fig. B-1). Minimum daily temperatures at LS and CM were consistently lower than at PM, perhaps reflecting the increasing influence of nocturnal, cold air drainages further down the valley. PM usually experienced higher daytime maximums. Likewise, the cumulative growing degree-days from March 1st – October 31st, calculated by summing up the mean daily temperature departures from 10^{o} C, also reflect that CM was the coolest and PM was the warmest (Table B-1).

Table B-1. Growing degree days from March 1st to October 31st.

Year	LS	PM	CM
2001	2364	2439	2232
2002	2553	2650	2382
2003	2564	2718	2437

While there were some significant differences in the temperatures, the different site characteristics probably had a microclimatic influence on these results. CM temperatures were measured at 3 m height inside the mesquite woodland. LS temperatures were measured at 2 m height, surrounded by a mesquite shrubland, and 2 m temperatures at PM were over an abandoned agricultural field. All of the above site temperature differences, except for nighttime minimum temperature, could arguably be attributed to these differences in vegetation cover. Finally, the first freeze events of fall and the last freeze events of spring were remarkably similar across all sites (Table B-2). This was likely due to the influence of large-scale frontal air masses which are primarily responsible for the import of cold arctic air into the area. This final result is probably the most important result for riparian water use because the length of growing season almost entirely constrains the water use of the mesquite and, possibly, the other important vegetation communities.

Table B-2. The dates (Julian day) of the last freeze of spring and first freeze of fall for all met sites.

	Lewis Springs		Palominas		Charleston Mesquite	
Year	last freeze	first freeze	last freeze	first freeze	last freeze	first freeze
2001	126	286	125	288	126	286
2002	142	277	123	277	142	277
2003	132	299	108	300	131	300

While there were some small differences in air temperature within the SPRNCA, the greatest differences were found between the riparian area and outside of the riparian valley on the San Pedro valley floor (Fig. B-2). For example, minimum daily temperatures at the Fort Huachuca Met Support office (elev. 1422 m) were much warmer (more than 10^{o} C during many months) than the LS site. This resulted in a higher mean temperature despite the higher elevation and the cooler maximum temperatures of the Fort. Future studies that employ eco-hydrological models driven by meteorological forcing should use data collected within the riparian valley or use these data to build regression relationships with met stations outside of the riparian valley.

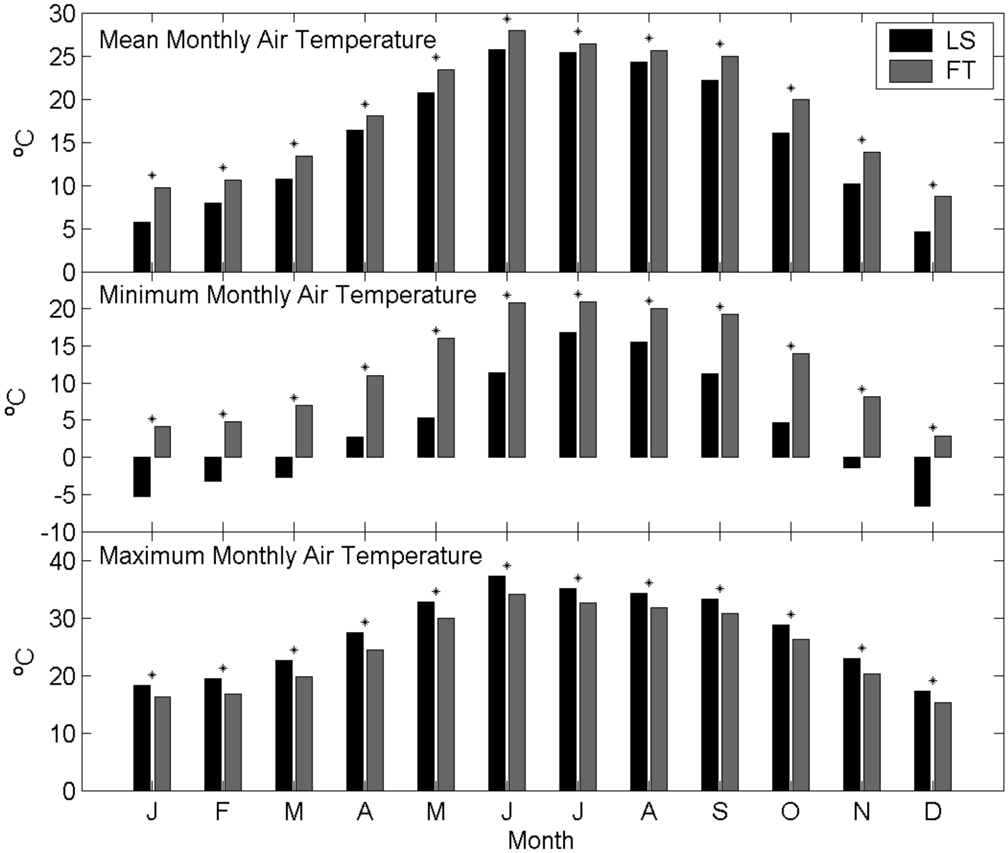

Figure B-2. The 2001 – 2003 average monthly mean, minimum, and maximum daily air temperatures for the Lewis Springs (LS) and the Fort Huachuca (FH) met sites. Averages that were significantly different (p = 0. 05) from the each other are indicated by an asterisk.

We computed a standard reference crop evaporation rate (ET_o, Brown, 1889; http://ag.arizona.edu/azmet/et2.htm) using the temperature, relative humidity, solar radiation, and wind speed to compare how atmospheric evaporation demand might vary. There were only slight differences between LS and CM, but at PM ET_o was considerably higher (Fig. B-3 and Table B-3). Differences in wind speed between the sites, with mean wind speeds about 35% higher at PM, were primarily responsible for the differences in ET_o.

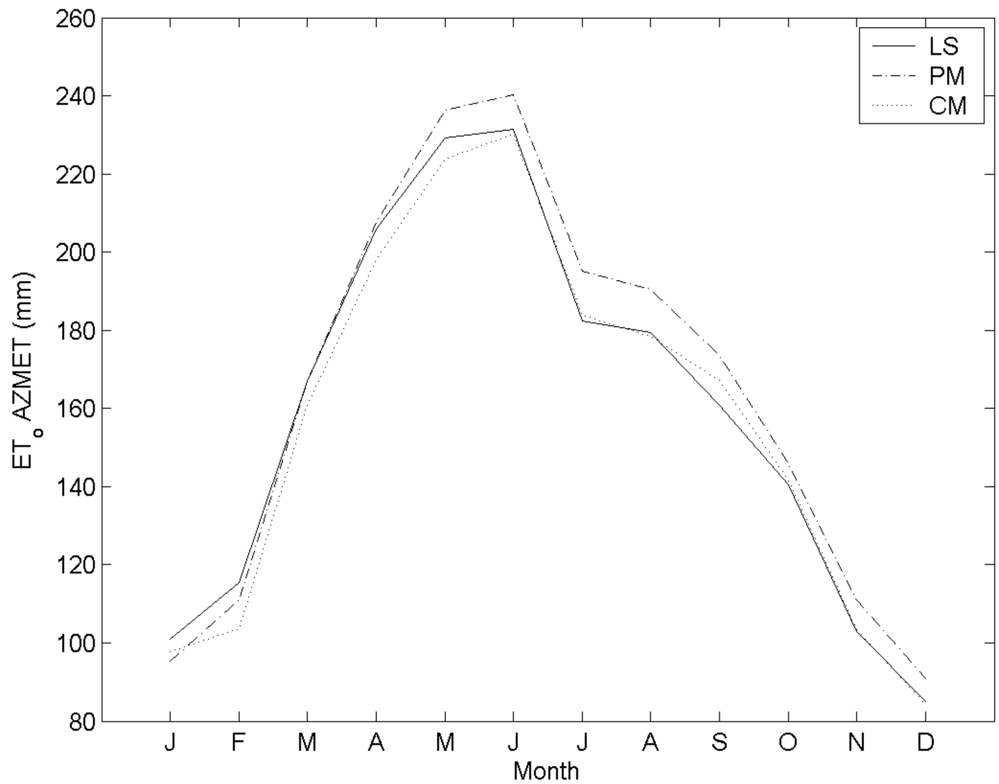

Figure B-3. 2001-2003 average total monthly reference crop evaporation (ET$_o$) computed using the AZMET method.

Table B-3. 2001-2003 average total monthly reference crop evaporation (ET$_o$) computed using the AZMET method. Units are in mm.

	LS	PM	CM
Jan	10.1	9.5	9.8
Feb	11.5	11.1	10.4
Mar	16.7	16.7	16.1
Apr	20.6	20.8	19.8
May	22.9	23.6	22.4
Jun	23.1	24	23
Jul	18.2	19.5	18.4
Aug	17.9	19	17.8
Sep	16.1	17.4	16.7
Oct	14	14.6	14.2
Nov	10.3	11.1	10.3
Dec	8.5	9.1	8.4
Total	189.9	196.4	187.3

In conclusion, we do not believe that the met conditions observed at these three sites were sufficiently different to invalidate our approach of up-scaling ET measurements to estimate water use for the entire SPRNCA. Growing season lengths as determined by freezes in the spring and fall were nearly equivalent, and this constrains much of the groundwater use by SPRNCA vegetation. We found that the PM site was considerably windier and this might be an important consideration of future studies that employ ET models based on wind speed measurements. We note that regular calibration of the Fort's met sensors during this study was not performed so the results of this study cannot be verified until an intercomparison of the sensors is performed.